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SCENARIO-BASED SYSTEMS ENGINEERING APPLICATION TO MINE WARFARE

by

Team Mine Warfare (MIW) 2015
Cohort 311-132M

December 2015

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This report builds upon the Team MIW 2014 capstone report in comparing legacy and future mine countermeasures capabilities. The Mark 18 Modification 2 Unmanned Underwater Vehicle was compared to the planned Littoral Combat Ship MCM Mission Package Increment 1 Remote Mine Hunting System as well as the legacy MCM 1 and CH-53E. The Measures of Effectiveness (MOE) utilized were Area Clearance Rate Sustained and minefield percent clearance. A tailored systems engineering approach based on a modified SE "Vee" model was utilized to identify stakeholder requirements, conduct analysis of functional and physical architectures, and use these resulting artifacts to modify an existing model. A design of experiments process was utilized to analyze input variables for relationships to the MOEs and compare resulting MOEs from the various configurations. A cost analysis was then performed and, with the performance data, was used to evaluate the relative value of the various configurations. Conclusions from the data are presented along with recommendations for future analysis.

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ABSTRACT

This report builds upon the Team MIW 2014 capstone report in comparing legacy and future mine countermeasures capabilities. The Mark 18 Modification 2 Unmanned Underwater Vehicle was compared to the planned Littoral Combat Ship MCM Mission Package Increment 1 Remote Mine Hunting System as well as the legacy MCM 1 and CH-53E. The Measures of Effectiveness (MOE) utilized were Area Clearance Rate Sustained and minefield percent clearance. A tailored systems engineering approach based on a modified SE "Vee" model was utilized to identify stakeholder requirements, conduct analysis of functional and physical architectures, and use these resulting artifacts to modify an existing model. A design of experiments process was utilized to analyze input variables for relationships to the MOEs and compare resulting MOEs from the various configurations. A cost analysis was then performed and, with the performance data, was used to evaluate the relative value of the various configurations. Conclusions from the data are presented along with recommendations for future analysis.

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LIST OF ACRONYMS AND ABBREVIATIONS

AT&L	acquisition, technology, and logistics
AAW	air warfare
ACR	area coverage rate
ACRS	area coverage rate sustained
ALMDS	airborne laser mine detection system
AMCM	airborne mine countermeasures
AMNS	airborne mine neutralization system
Ao	operational availability
AoA	analysis of alternatives
AOR	area of regard
ARMS	autonomous remote mine-hunting simulation
ASW	anti-submarine warfare
ASuW	anti-surface warfare
AUV	autonomous hunting vehicle
CCDR	combatant commander
CJCS	Chairman of the Joint Chiefs of Staff
COA	course of action
CONOPS	concept of operations
CVBG	carrier battle group
CYW	cyber warfare
DAG	Defense Acquisition Guidebook
DOD	Department of Defense
DODD	Department of Defense directive
DODI	Department of Defense instruction
DOE	design of experiment
DOTMLPF	doctrine, organization, training, materiel, leadership, personnel, and facilities
EOD	explosive ordnance disposal
FFBD	functional flow block diagram
HA/DR	humanitarian assistance/disaster relief

Inc	increment
INCOSE	International Council on Systems Engineering
IOC	initial operating capability
ISR	intelligence, surveillance, and reconnaissance
JP	Joint Publication
KPP	key performance parameter
LCC	life-cycle cost
LCS	littoral combat ship
LMW	littoral and mine warfare
M&S	modeling and simulation
MANA	map aware non-uniform automata
MBSE	model-based systems engineering
MCM	mine countermeasure
MCTSSA	Marine Corps Tactical Systems Support Activity
MILCO	mine-like contact
MILEC	mine-like echo
MIW	mine warfare
MK	mark
Mod	modification
MOE	measures of effectiveness
MP	mission package
MSSE	Masters of Science Systems Engineering
MSES	Masters of Science Engineering Systems
NDP-1	Navy Doctrine Publication 1
NATO	North Atlantic Treaty Organization
NM	nautical mile
NMAWC	Naval Mine and Anti-Submarine Warfare Command
NOLH	nearly orthogonal Latin hypercube
NPS	Naval Postgraduate School
NRC	National Research Council
NSW	naval special warfare
NWP	naval warfare publication

O&S	operating and sustainment
PAC	Pacific
PEO	Program Executive Officer
PMA	post mission analysis
POR	program of record
REMUS	remote environmental monitoring unit system
Ret	retired
RHIB	rigid hulled inflatable boat
RMMV	remote multi-mission vehicle
RMS	remote mine hunting system
SASC	senate armed services committee
SCM	search, classify, and map
SE	systems engineering
SLOC	sea line of communication
SME	subject matter expert
SPAWAR	Space and Naval Warfare
SSC	SPAWAR System Center
T&E	test and evaluation
TTP	tactics, techniques, and procedures
U.S.	United States
USD	Under Secretary of Defense
USV	unmanned surface vehicles
UUV	unmanned undersea vehicle
VV&A	verification, validation, and accreditation
VAMOSC	visibility and management of operating and support costs
VSW	very shallow water
WRT	with regard to

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EXECUTIVE SUMMARY

The National Research Council's Committee for Mine Warfare Assessment (2001) reports: "Since World War II, U.S. naval forces have suffered significantly more physical damage and operational interference from sea mines than from air, missile, and submarine attacks" (2). This threat continues today, and effective methods for fulfilling the search, identification, classification, and neutralization functions are needed.

The United States (U.S.) Navy currently employs specially designed ships to satisfy the search through neutralization aspects of the mission (PEO LMW 2009), but the Avenger class of mine countermeasure (MCM) ships is aging and reaching end of life. The current tactics also place the sailors manning these ships in danger, as the MCMs traverse the minefield during their operations (PEO LMW 2009). As a replacement solution the littoral combat ship (LCS) has a specifically designed MCM mission package (MP) which allows operators the ability to employ a remote mine hunting system (RMS) to search, identify and classify mines in a safer manner through the removal of the warfighter from the minefield (PEO LMW 2009). The RMS is an Unmanned Underwater Vehicle (UUV) that performs sensing operations to find mines. Neutralization is carried out by the SH-60S. This report examines the potential use of the autonomously operated Mark 18 Modification 2 (MK18 Mod 2) as an alternative or supplemental search asset to the proposed LCS MCM MP RMS.

The RMS is a large UUV launched from the mission bay of the LCS. According to Avenger class platform MCM Embark Officer Mark Sergi, it has been under development for many years as part of the LCS MCM MP Program of Record (POR), but has reportedly suffered reliability and detection problems (Mark Sergi, personal comm.). According to MK18 Mod 2 project team member Michael Stuckenschnieder, the MK18 Mod 2 is a small UUV currently operated by EOD units in the 5th Fleet Area of Regard (AOR). It is smaller, slower, and cheaper than the LCS MCM MP RMS, but it is currently operational with planned incremental improvements already programmed (Mark Sergi, personal comm., Michael Stuckenschnieder, personal comm.). The MK18

Mod 2 is battery powered and the LCS MCM MP RMS is powered by a diesel engine (Mark Sergi, personal comm., Michael Stuckenschnieder, personal comm.).

In conducting this research, the team first embarked upon a literature review to develop an understanding of legacy and current MIW systems, operations, and the MK18 Mod 2. This review was supplemented with information from stakeholders and subject matter experts (SME) during an analysis of their needs in development of a problem statement, project scope and requirements of the mission thread which could be satisfied within the constraints of the capstone project. As this study is a follow on effort to the 2014 MIW capstone project, the recommendations provided by that study identified some gaps in capabilities, systems, and functions, and this team extended the research focus with the inclusion of the MK18 Mod 2 into the LCS MCM MP. The primary research questions were developed using the established metrics that the U.S. Navy uses to measure the effectiveness of an MCM capability (source: 2014 MIW capstone) and applied to the MK18 Mod 2 in a comparative analysis.

The goal of the 2015 MIW capstone team was to provide meaningful data to decision makers regarding the possible employment of the MK18 Mod 2 in place of the LCS MCM MP RMS. While the decision to model the MK18 Mod 2 in lieu of the LCS MCM MP RMS had already been made, this substitution was later suggested as a possible alternative by both the Senate Armed Services Committee's (SASC's) ranking member and chairman in a letter to the Department of Defense (DOD) (Rear Admiral Rick Williams, USN (Ret), personal comm.). This study was restricted by its need to remain unclassified; therefore, SMEs provided representative ranges of data for the various systems.

Using a tailored systems engineering process, the team first performed an analysis of stakeholder needs to determine the requirements for our study and these were scoped using the project constraints as detailed above. Systems analysis involved gaining understanding of the MCM missions, operational characteristics of the MK18 Mod 2, and also the decomposition and operation of the model provided to the 2015 MIW team for use as the follow on study to the 2014 MIW team's efforts. Building upon and extending the 2014 MIW capstone team's work, the 2015 MIW study added the possible mission

configurations utilizing the MK18 Mod 2 into the operational scenario configurations modeled. The 2015 MIW team implemented a modeling approach which allowed for the simulation of varying quantities of MK18 Mod 2s and associated support activities to leverage the existing model for consistency of data. The resultant data produced by the multiple model variants was then statistically analyzed for use in the comparative analyses with the other MCM mission options previously modeled.

A primary research question examined in this study was to determine if the MK18 Mod 2, when used as the search asset, could equal or surpass the overall mission effectiveness when compared with the legacy MCM methods or current LCS MCM MP. To realize this goal, 11 operational scenarios (which involved varying the quantities of the MK18 Mod 2 from one to 10, and 12) were modeled in the same manner as the 2014 MIW capstone project to provide a valid comparison using unclassified data.

These 11 variations of the LCS using the MK18 Mod 2 leveraged the base ExtendSim model of the LCS version 3 of the 2014 MIW capstone, and extended it to support the simulation of the MK18 Mod 2 performance and mission support characteristics. A mine clearance design reference mission area of 10 nautical miles (NM) by 10 NM containing bottom mines in deep water (depth of greater than 200 feet) was used for data consistency between the efforts. The MK18 Mod 2 scenarios modeled produced data for the calculation of SME and stakeholder interest of the measures of effectiveness (MOE) for comparison with the prior study of area coverage rate sustained (ACRS) and percentage of mines cleared (% clearance) (source: 2014 MIW capstone). An excursion to investistigate the 2015 MIW team's hypotheses surrounding the MK18 Mod 2's effectiveness in the isolation of the search portion of the mission was also performed.

Using a design of experiments (DOE) approach, each MK18 Mod 2 model variant was run using broad ranges of 20 input parameters (which includes operational factors such as surface search speed, turn time at end of track, and time to recover equipment by the LCS) instituted by the 2014 MIW team as provided by the MK18 Mod 2 SMEs and stakeholders to maintain the unclassified nature of the study. These parameters allowed for the characterization of the functions and activities applicable to the MCM mission

(source: 2014 MIW capstone) and determination of the significant variables affecting the response MOE of interest, ACRS and percent clearance, to focus our research. A table with all factors, including their value ranges, is presented in the body of this report.

From the ACRS plot in Figure 1, it can be seen that an LCS configuration 4M using 4 MK18s exceeds the ACRS performance of both the legacy 2a and LCS configuration 3 by 0.70 and 1.25 respectively. Percent clearance was seen to drop below that of legacy configuration 2a and LCS configuration 3 values by approximately 6.5%. This can be attributed to the difference in ranges used for surface probability of detection for the previous project (0.70 to 0.90) and those used for this project and the MK18 (0.60 to 0.85). With a lower range it was expected and verified by simulation results that a lower percent clearance would be seen. When surface probability of detection increases, more mines are detected, resulting in a slight reduction in ACRS. Configurations of 1 through 10 MK18s is the primary focus of this study, but after plotting the results in the initial plots of Figure 1 for up to 10 MK18s, it was noted that as additional MK18s were added to the simulation, the ACRS increases began to diminish. A run simulating 12 MK18s was then conducted in order determine if there was a convergence. This single excursion did not provide enough clarity to determine at what point increases in numbers of MK18s results in no significant ACRS increase.

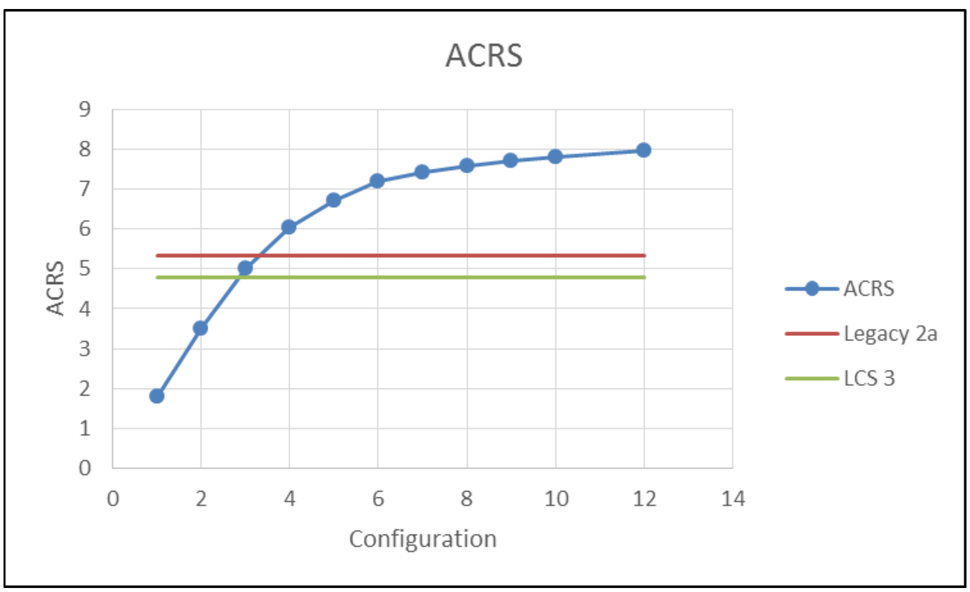

Figure 1. Mean of ACRS vs. Configuration

During this DOE, the focus was to determine which factors had the greatest impact on the response variables of ACRS and percent clearance. As shown in Table 1, the top three significant factors affecting each configuration for ACRS are shown, and these factors change as the number of MK18s increase. As these numbers go up, time to replenish and actual search speed become less important and the ability of the MK18 to correctly classify non-mine targets becomes the most significant, followed by the overall probability of detection.

Table 1. ACRS Top Three Significant Factors

Configuration	1	2	3
1M	S_Replenish_hr	S_SearchSpeed_kt	S_NumHntTrk_pNM
2M	S_Replenish_hr	S_SearchSpeed_kt	S_NumHntTrk_pNM
3M	S_Replenish_hr	S_SearchSpeed_kt	S_NumHntTrk_pNM
4M	S_Replenish_hr	S_Pcnn	S_SearchSpeed_kt
5M	S_Pcnn	S_Replenish_hr	S_SearchSpeed_kt
6M	S_Pcnn	S_Pd	S_Replenish_hr
7M	S_Pcnn	S_Pd	A_RRecoverT_hr
8M	S_Pcnn	S_Pd	A_RRecoverT_hr
9M	S_Pcnn	S_Pd	A_RRecoverT_hr
10M	S_Pcnn	S_Pd	A_RRecoverT_hr

The top three significant factors for percent clearance are presented in Table 2. Surface probability of classifying a MILEC as a MILCO (S_Pcmm) dominates the top position with airborne probability of identifying a MILCO as a mine (A_Pimm) and Surface Probability of detecting a MILEC (S_Pd). Again, since the air asset was not the primary focus of this project S_Pd was chosen as a factor of interest over A_Pimm although both factors had t ratios that were very close together. After close analysis of significant factors for both ACRS and % clearance, it can be seen that effective numbers

of MK18s (four or greater) are most significantly impacted by the ability of the sensor and operators to detect and classify targets.

Table 2. Percent Clearance Top Three Significant Factors

Configuration (# MK18)	1	2	3
1M	S_Pcmm	A_Pimm	S_Pd
2M	S_Pcmm	A_Pimm	S_Pd
3M	S_Pcmm	S_Pd	A_Pimm
4M	S_Pcmm	A_Pimm	S_Pd
5M	S_Pcmm	A_Pimm	S_Pd
6M	S_Pcmm	A_Pimm	S_Pd
7M	S_Pcmm	A_Pimm	S_Pd
8M	S_Pcmm	A_Pimm	S_Pd
9M	S_Pcmm	A_Pimm	S_Pd
10M	S_Pcmm	A_Pimm	S_Pd
12M	S_Pcmm	A_Pimm	S_Pd

Mission costs were also compared for each MK18 Mod 2 configuration evaluated using point estimates derived from operation and sustainment (O&S) data provided by stakeholders and SME. The MK18 Mod 2 configurations were assumed to consist of a single rigid hull inflatable boat (RHIB) for every two MK18 Mod 2 in transit. Total mission costs of the legacy and current LCS variants used the same point estimates as the 2014 MIW team for consistency of data. Of note in the resulting cost analysis was that the O&S costs for the currently planned LCS MCM MP resulted in a lower total per-mission cost than the other tested MCM variants. Key to this finding is the broader range of probability of detection (Pd) provided to the team for the MK18 Mod 2 which produced a larger target list and the resulting expenditure of neutralizers on non-mines. However, overall MK18 value was shown to be greater than legacy or LCS MCM MP configurations for MK18 numbers of four or more as shown in Figure 2. Figure 2 also

shows that six MK18s had the highest value, but all MK18 configurations over four provided more mission value than either the legacy or the LCS MCM MP.

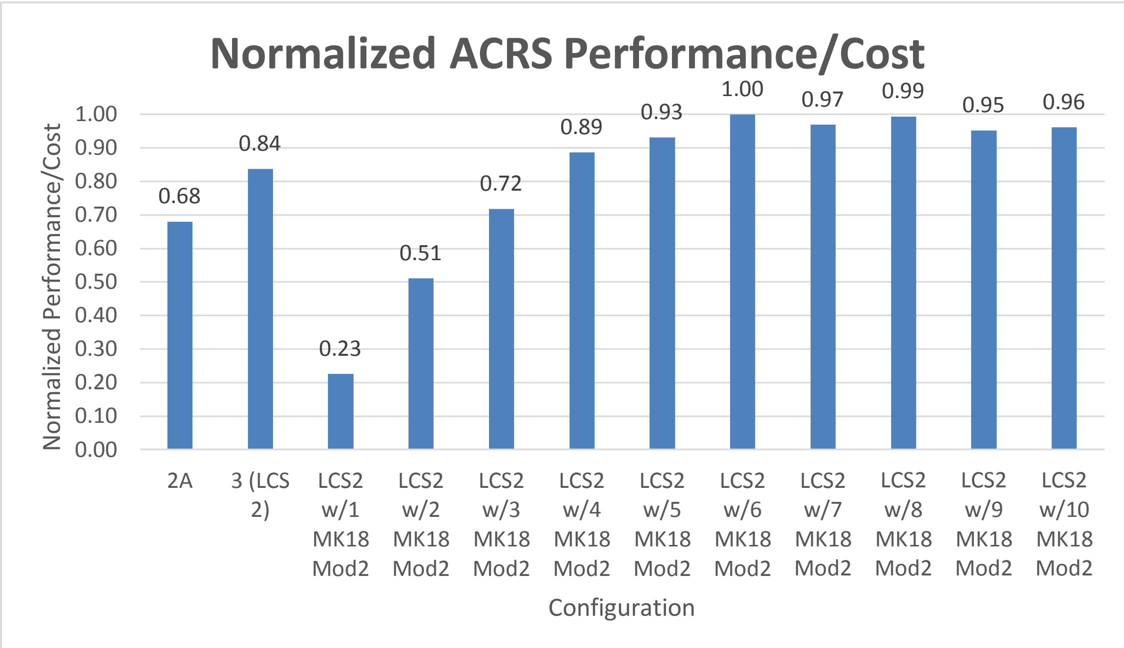

Figure 2. Configuration vs. Normalized ACRS Performance/Cost

This study has concluded that, in the specific scenario modeled with the unclassified data ranges utilized, the MK18 Mod 2 is an effective alternative search asset to the LCS MCM mission package and legacy MCM methods when implemented with four or more devices performing the search function in terms of ACRS performance. When effective numbers of MK18s are utilized, the ability of the MK18 to detect and classify the target has the biggest impact on both ACRS and percent clearance, meaning that if large numbers of MK18s are used, this is likely the area to concentrate on for improvements. Using the cost estimates for the analysis, based upon the data provided, variant 2 of the LCS with the MK18 Mod 2 performing the search function has been shown to have the highest ACRS performance/cost when four or more MK18s are utilized. Recommendations to improve the probability of detection and classification of the MK18 to equal or exceed those of the LCS MCM MP RMS will allow the MK18 Mod 2 to match or exceed the percent clearance performance of the RMS.

In order to fully capitalize on the effort put into this project, the model as developed this far needs to be replicated in a secure enclave and populated with classified data. This will allow for a realistic comparison between various solutions and should also consist of more detailed cost data than this project team had available. Future work is also recommended in expanding the operational scenario depicted in the current MCM model utilized by this capstone group, such as study of lane clearance missions, simulations of differing mine types, as well as changing the bottom depth. Other areas of consideration are further study into the existing scenario, such as investigations into the diminishing returns of added MK18s, or including in the simulation the ability to "share" RHIBs among the MK18s rather than require a separate RHIB for every pair of MK18s. Other autonomous vehicles exist that might also provide capability over the LCS RMS, and these should be investigated as well. Another approach could be to fully revisit the underlying assumptions of the existing model based on stakeholder feedback, for example, to conduct all search prior to beginning neutralization, and then selecting the lowest density corridor for clearance to minimize time required to conduct neutralization.

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I. INTRODUCTION AND BACKGROUND

This report provides the results of the evaluation of alternative defensive mine countermeasures (MCM) of the Littoral Combat Ship (LCS) fitted with the Mark (MK)18 modification (Mod) 2 Mission Package (MP) in comparison to the legacy Avenger class MCM ship (MCM 1), and the currently deployed LCS and associated remote mine hunting system (RMS). This study, conducted in part to satisfy the requirements of the Naval Postgraduate School (NPS) Master of Science in Systems Engineering (MSSE) and Master of Science in Engineering Systems (MSES) programs, followed a tailored systems engineering process described within the body of this report. The study has focused on furthering the understanding of legacy and future mine warfare (MIW), MCM capabilities and alternative solutions through extensive literature reviews, stakeholder and subject matter expert (SME) feedback incorporated into a model constructed following a structured systems engineering process to provide a method for comparative analysis. A preliminary stakeholder analysis framed the project objectives and was refined to form the project's scope and problem statement.

This introductory chapter provides background information on naval mine warfare in historical context, the progression of available technologies and practices evolving into the present day threat and potential counter-measures. To further the team's understanding of MIW and MCM missions, an extensive literature review of topics within the research problem space was performed allowing for refinement of the specific MIW/MCM problem area leading to the focused problem statement. The chapter concludes with the systems engineering approach implemented within the research study.

A. BACKGROUND

Sea mines have been an integral component of naval warfare and have been used tactically since the colonies fought the British Fleet continuing through the present. Although relatively inexpensive to manufacture and employ in battle, they continue to show effectiveness in both offensive MIW and defensive and MCM applications countering the dominance of a superior navy. While particularly useful as an asymmetric

weapon, they are effective against any navy regardless of the relative strengths. “Since World War II, U.S. naval forces have suffered significantly more physical damage and operational interference from sea mines than from air, missile, and submarine attacks” (National Research Council, Committee for Mine Warfare Assessment 2001, 2), depicted in Figure 1.

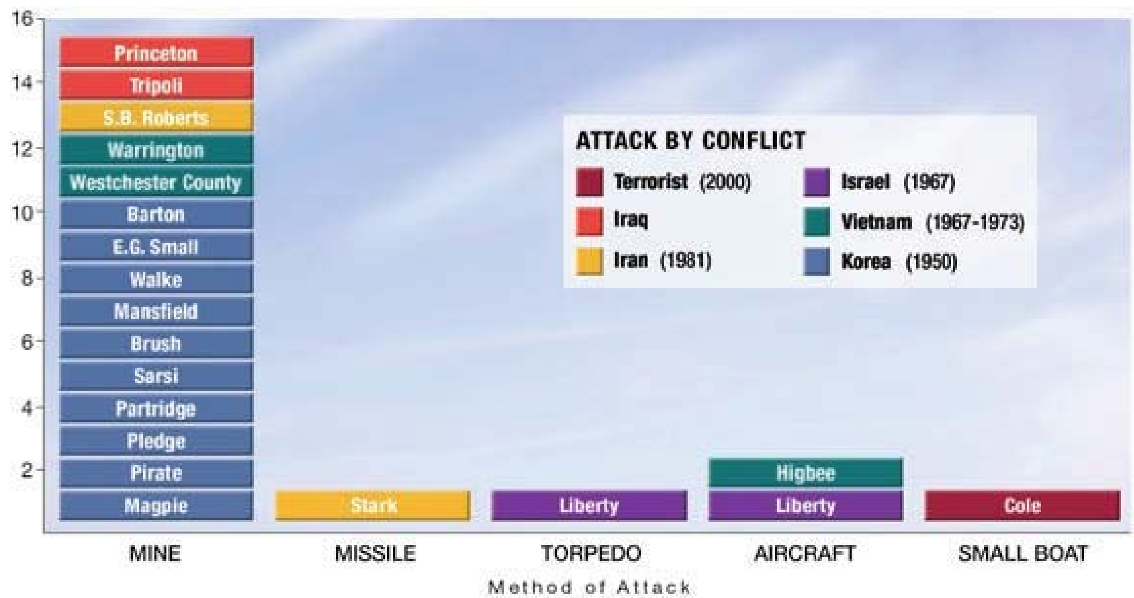

Figure 1. U.S. Navy Mine Casualties 1950–1991 (source: PEO LMW 2009)

Rather than directly engaging the United States (U.S.) Navy, mines have proven to be an effective strike capability for hostile forces employing asymmetric tactics, as demonstrated in the Korean, Vietnam and Gulf wars. When used tactically, sea mines can provide a delay of attack or impede the availability and movement of supplies, forcing recalculation of strategic and tactical plans. A general consensus shared among the available research literature is that although MIW and MCM tactics have remained relatively static for the duration of their employment to present, technology advances will transform the capabilities and act as multipliers in the potential effectiveness of future mine warfare (Naval Mine Warfare Engineering Activity 1991; Commander Joint Chiefs of Staff 2011; Committee for Mine Warfare Assessment 2001).

Through the literature reviews, the team has concluded that as with offensive MIW tactics, techniques, and procedures (TTP), defensive MCM methods remain relatively static in application as well as relying primarily on intelligence, surveillance, and reconnaissance (ISR) for mitigation of the mine threat. With the proliferation of adversaries capable of implementing sophisticated and hard-to-find naval mines, the need for ISR will remain critical for the U.S Navy to remain the dominant sea power (Department of the Navy, Office of the Chief of Naval Operations Septemeber 2010). In conjunction, the methods and technologies employed for MCM will have to match or exceed those capabilities that exist on the offensive MIW. As stated in the U.S. Navy Mine Countermeasures Familiarizer report, historically mines have not been perceived as the target but rather as an obstacle. As a result, attention and funding during non-combatant times for offensive MIW and defensive MCM tactics remain relatively unchanged from the earliest implementations (Naval Mine Warfare Engineering Activity 1991). Naval mines though have become increasingly sophisticated and consist of differing deployment and actuation methods, each requiring a unique approach for identification, classification and ultimately neutralization complicating the present and emerging MCM mission thread (Naval Mine Warfare Engineering Activity 1991).

From the end of the Vietnam War through the 1990s, little attention was paid to the modernization of the mine warfare assets, and fleet resources remained static (Melia 1991). Additionally, the U.S. effectively facilitated the ability of our adversaries to implement effective mine warfare tactics against our strengths by allowing the programs to wane in non-conflict periods by not recognizing the need for continued diligence in MIW and MCM efforts. As the new 21st century naval warfighting concepts of *Forward … from the Sea* (Department of the Navy 1994) were being developed in the mid-1990s, the need for enhanced littoral capabilities was one item identified, providing the opportunity to shape the framework of future MIW and MCM capabilities.

To address these issues the U.S. Navy planned to address the MIW/MCM mission in a holistic manner, placing new emphasis on the entirety of the mission doctrine, organization, training, materiel, leadership, personnel, and facilities (DOTMLPF) through the establishment of MIW as a major naval warfare area (National Research Council,

Committee for Mine Warfare Assessment 2001) with upgraded certification, training, education and officer career planning. Materiel improvements are being implemented through the replacement of the ageing Avenger class ships and airborne assets currently providing MIW/MCM capabilities with specific MP configurations of the LCS and associated remotely controlled airborne and seabound assets. As noted in the National Research Council (NRC) Committee for Mine Warfare Assessment, *Naval Mine Warfare Operation and Technical Challenges for Naval Forces*, the LCS MIW/MCM MP currently in service do not execute the mission in similar fashion to the Avenger class ships, and current capabilities have yet to be proven as effective as the legacy configurations (National Research Council, Committee for Mine Warfare Assessment 2001). In the current budgetary constrained environment, decisions on how to allocate funding between sustainment of legacy assets and development and deployment options of LCS MP capabilities must be made by leadership to provide adequate MIW/MCM capabilities to the fleet while remaining fiscally responsible. Our study contributes to that effort through the modeling of critical measures of effectiveness (MOE) of stakeholder systems of interest (Program Executive Office Littoral and Mine Warfare 2009).

This project is primarily concerned with investigating area coverage rate sustained (ACRS) and percent clearance. ACRS is defined as the area covered divided by the total time to clear that area over a 24-hour period. Percent clearance is defined as the number of mines neutralized divided by the number of mines existing in the minefield.

B. LITERATURE REVIEW/RESEARCH

Current MCM capability consists of the MCM 1 Avenger class vessels. These vessels are planned to be completely retired by 2024 (Program Executive Office Littoral and Mine Warfare 2009). The LCS MCM mission package is the planned successor. It is unknown how the LCS mission package will perform regarding both the total capability of the mission package and how it will compare with existing MCM Avenger class capability. According to the MIW community, the need to compare the developmental Mark 18 Mod 2 and other autonomous mine detection systems to RMS used in the LCS MCM mission package is required.

The research methodology included a literature review which provided background on mine warfare basics, mine countermeasure activities, and the history of MIW to better understand the need for MCM improvements. The purpose of the literature review was to gain a comprehensive overview and understanding of the history and back ground of MCM. This was necessary to understand the problem and ask the necessary questions to make the correct assumptions for successful model modification. The project team was not familiar with any aspect of MIW before starting this project. Without this understanding the team would have been unable to successfully comprehend the problem and craft a solution to satisfy stakeholder's needs and project objectives. This research allowed for critical capability identification, identification of a realistic mine clearance area, and identification of the capabilities, as well as the limitations, of the MK18 Mod 2 and the LCS MCM mission package. Prior to conducting any modification to the existing model simulation, technical information and details were required to support initial project research.

Mines have been employed on a small scale since the time of the Revolutionary War and used on a larger scale since the Civil War. Due to their relatively low cost, ease of employment, and battlefield effectiveness mines remain "easy to lay and difficult to sweep; their concealment potential is strong; their destructive power is high; and the threat value is long-lasting" (Erickson, Goldstein and Murray 2009, 1). Typical mine construction is "composed of different combinations of explosive charges, firing mechanisms, sensors, and housings." "They can be described by their position when planted as bottom, moored, previously moored floating, or as drifting mines" (Melia 1991, 5). The most commonly used mines historically are contact mines that are typically moored. These moored mines can be countered by severing the tether and allowing them to rise to the surface for destruction. Bottom mines that consist of influence mines are target and water depth dependent. Modern mines often contain sophisticated control systems that contain ship counters, delay instruments, and self-destruct capabilities. The advent of microcomputers has seen the rise of "smart" mines that are capable of targeting specific types of ships and can turn themselves on and off to avoid detection. (Melia 1991).

Mine Countermeasure activities are classified in one of two categories; passive and active. Passive MCM activities consist of efforts to avoid mines and detonations while active efforts consist of offensive activities with the goal of mine detection, neutralization, and collateral damage reduction.

A review of legacy mine warfare capability was initially performed through the review of documents referenced and used by the previous MIW Capstone team. “The Avenger class ships perform legacy mine sweeping and hunter-killer capabilities to find, classify, and destroy moored and bottom mines with sonar and video systems, cable cutting devices, and mine detonating devices that are capable of being released and detonated by remote control” (Office of Corporate Communication (SEA 00D) 2014, 1). These ships are fiberglass sheathed, constructed with a wooden hull and are capable of conventional mine sweeping methods. (Office of Corporate Communication (SEA 00D) 2014)

Based on the initial problem scope, the MK18 Mod 1 Swordfish and primarily the MK18 Mod 2 Kingfish autonomous unmanned undersea vehicle (UUV) capabilities were researched. Both designs followed from the Remote Environmental Monitoring Unit System (REMUS) Autonomous Hunting Vehicle (AUV) developed in the 1990s. “The REMUS 100 was used by the U.S. Navy for shallow water mine detection” (Remote Environmental Monitoring Unit System (REMUS) n.d., 1). The MK18 Mod 1 Swordfish UUV, which was based on the REMUS 100, is “designed to Search, Classify, and Map (SCM) the very shallow water (VSW) region (10-40 ft.)” (Remote Environmental Monitoring Unit System (REMUS) n.d., 1). It is capable of conducting low-visible search, classification, and mapping operations in support of MCM activities. The MK18 Mod 2 Kingfish UUV, which was based on the REMUS 600, reached full operational capabilities in 2008 (Naval Expeditionary Warfar 2010). It possesses an “increased area coverage rate (ACR), increased endurance, and will serve as a platform for advanced sensors” (Remote Environmental Monitoring Unit System (REMUS) n.d., 1). The MK18 Mod 2 Kingfish provides a wider search path, the detection of buried targets, and higher resolution imagery. The first MK18 Mod 2 Kingfish were deployed by the U.S. Navy to

the Middle East in July of 2012. They were tasked with search, classification, and mapping missions. Figure 2 details the components of the MK18 Mod 2 UUV.

Figure 2. MK18 Mod 2 Components (source: AUVAC 2015)

C. RESEARCH QUESTIONS

In order to fulfill the stakeholder's needs, research questions were identified to formulate the MIW problem and develop the topic. These questions provided a guideline for scoping and defining the problem.

How adequately does the current MCM force address the critical operational capabilities needed now?

The Avenger class MCM 1 is the current force used in MIW/MCM missions. Obtaining the metrics for the MCM 1 will provide the potential gaps by understanding

the concept of operations (CONOPS), capabilities, and the desired capabilities for successful MIW/MCM missions.

What capabilities and limitations does the projected future force have regarding its ability to address critical operational capabilities, as well as cost?

The LCS is the future force that will be used in MCM missions. Obtaining the preliminary metrics will provide the potential gaps by understanding the CONOPS, capabilities, and the desired capabilities for successful MIW/MCM missions.

What is the appropriate number of MK18 Mod 2 platforms to search for mines within a 10x10 grid (100 NM^2) scenario compared to the LCS MIW package?

When releasing one or many MK18 Mod 2 UUVs into the given scenario, it is important to determine which combination has the highest ACRS and percent clearance values for the overall mission with respects to searching.

What are the metrics used to determine the success of MCM?

Obtaining and narrowing down from the 38 factors that the 2014 MIW team utilized, these metrics will help to understand the CONOPS, capabilities, and the desired capabilities for successful MIW/MCM missions with respects to ACRS and percent clearance.

What is the effectiveness and cost of the MK18 Mod 2 at which it could match or exceed the LCS MP1 and legacy Avenger class MCM mission packages overall?

Obtaining the effectiveness and cost of the MK18 Mod 2 will help to determine how many UUVs would need to be implemented during a search function when compared to the LCS MP1 and legacy Avenger class MCM mission packages. ACRS and percent clearance values would be used to determine the best solution.

D. PROBLEM

Mine warfare has been a factor in naval conflicts since the Revolutionary War, and since World War II has resulted in greater U.S. ship losses than any other weapon type (National Research Council, Committee for Mine Warfare Assessment 2001). After

every major conflict, U.S. forces have neglected the development of mine warfare and its TTPs until the next incidence of mine usage (Melia 1991). Effective MIW capabilities are necessary to ensure U.S. and coalition forces access to contested waters in order to maintain sea lines of communication (SLOC). Current budgetary pressures require naval forces to be judicious with their funding in order to assure effective MIW capabilities against emerging and evolving threats. Asymmetric threats from state and non-state actors exist; the naval mine continues to be an effective asymmetric threat (National Research Council, Committee for Mine Warfare Assessment 2001).

E. CHAPTER SUMMARY

Sea mines have been used throughout history both defensively and offensively as a deterrent against opposing naval forces. Mines can be used to delay attack and impede resupply. Although tactics have remained fairly static over the years, many advancements in technology have the ability to transform these capabilities to act as force multipliers. By allowing the modernization of mine warfare assets to become static in periods of non-conflict the U.S allowed adversaries to gain an advantage. The U.S. Navy addressed these issues holistically through non-materiel means, such as establishing upgraded certification, training, education, and officer career planning. Materiel improvements were made by the planned replacement of aging Avenger class ships and airborne assets that are in current use providing MIW/MCM capabilities. LCS MIW/MCM mission packages currently in service do not perform missions in a similar manner as the Avenger class of ships. Additionally, there are concerns that these configurations may not be as effective as legacy configurations. Literature review revealed the planned retirement of existing legacy MCM 1 Avenger class vessels and the plan for the LCS with the MCM mission package to be the replacement. This team, having no prior experience with mine warfare, learned much from the literature review and the background of MIW and MCM.

Questions raised during the literature review range from how adequately the current MCM force addresses critical operational capabilities needed now to what capabilities and limitations exist with the future force regarding the ability to address critical operational capabilities and cost. Mine warfare has been employed in conflicts

since the Revolutionary War and since World War II has resulted in more U.S. ship losses than any other weapon type (National Research Council, Committee for Mine Warfare Assessment 2001). U.S. coalition forces require effective MIW capabilities to ensure access to congested waters and to maintain seal lines of communication. Effective means for achieving these goals are necessary within the confines of current budgetary pressures that require judicious funding considerations for emerging and evolving threats.

II. SE PROCESS AND MODELING METHODOLOGY

Systems engineering is a high level view of the solution space that covers the problem definition, analysis, design, construction, testing, production, operations, support, and removal from service. This is also known as “cradle to grave.” Systems engineering as a specific discipline in the modern age has been in existence since at least the 1940s and is still evolving today. This chapter explains several SE models that were considered, the tailored SE process, and the modeling methodology used to solve the problem.

A. INTRODUCTION

1. Systems Engineering Models

Systems engineering relies on models to describe the overall process. One of the early models used in describing the processes necessary for software engineering was the waterfall model. It is characterized by defined activities conducted sequentially, as shown in Figure 3. Each activity is completed prior to advancing to the next activity, and iteration only occurs between adjacent activities (Buede 2011). This model was first described for software engineering by Royce in 1970 in order to document how software engineering was being conducted. Royce then described how this model could be improved to address common issues, such as the need to return to non-adjacent steps when mistakes are found (Royce 1970). The waterfall model works best when the system requirements are fully known and understood upfront with no change over the system life cycle. Since the waterfall model is somewhat restrictive and inflexible, this was not chosen as the basis for the systems engineering process used for this project.

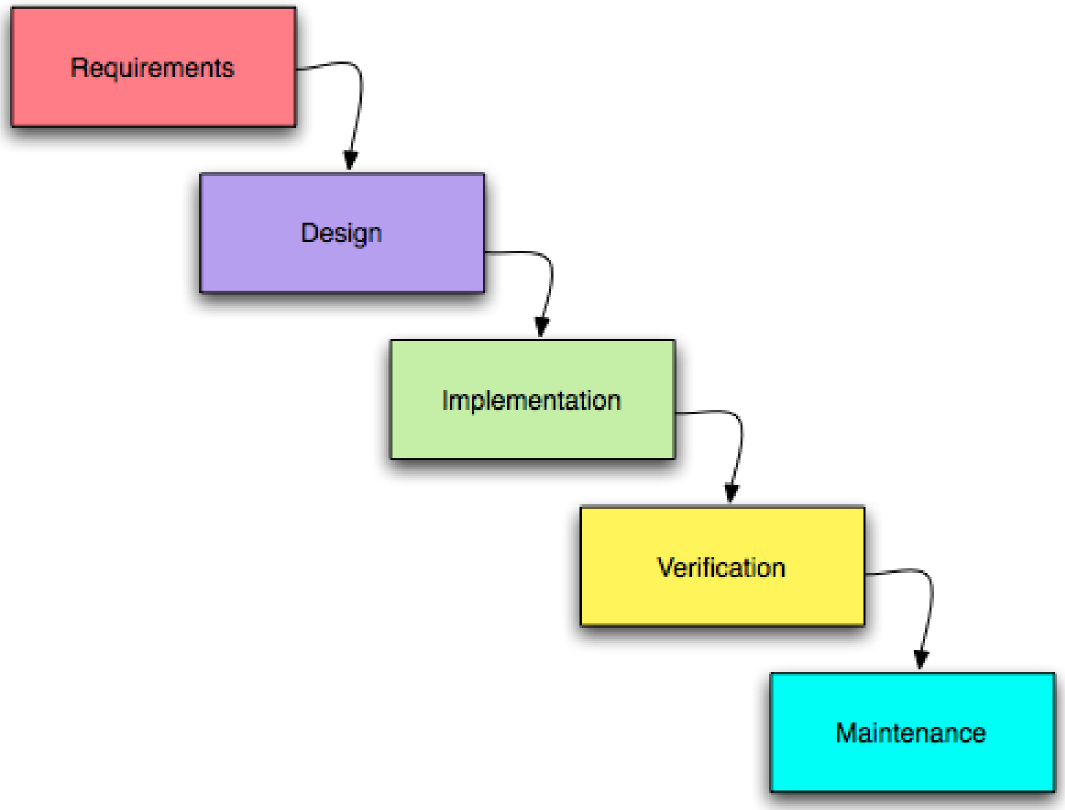

Figure 3. Waterfall Model (source: Blanchard and Fabrycky 2011)

Another model used in software engineering is the spiral process model as illustrated in Figure 4. This model attempts to correct for the rigidity of the waterfall model by repeatedly passing through iteration phases. The end of each phase results in the production of a prototype. Development in each cycle feeds the requirements of the next as lessons are learned. Ultimately, this results in an operational prototype leading to production. This model type was not chosen for this project as the restrictions of the course length do not allow for the creation of multiple prototypes.

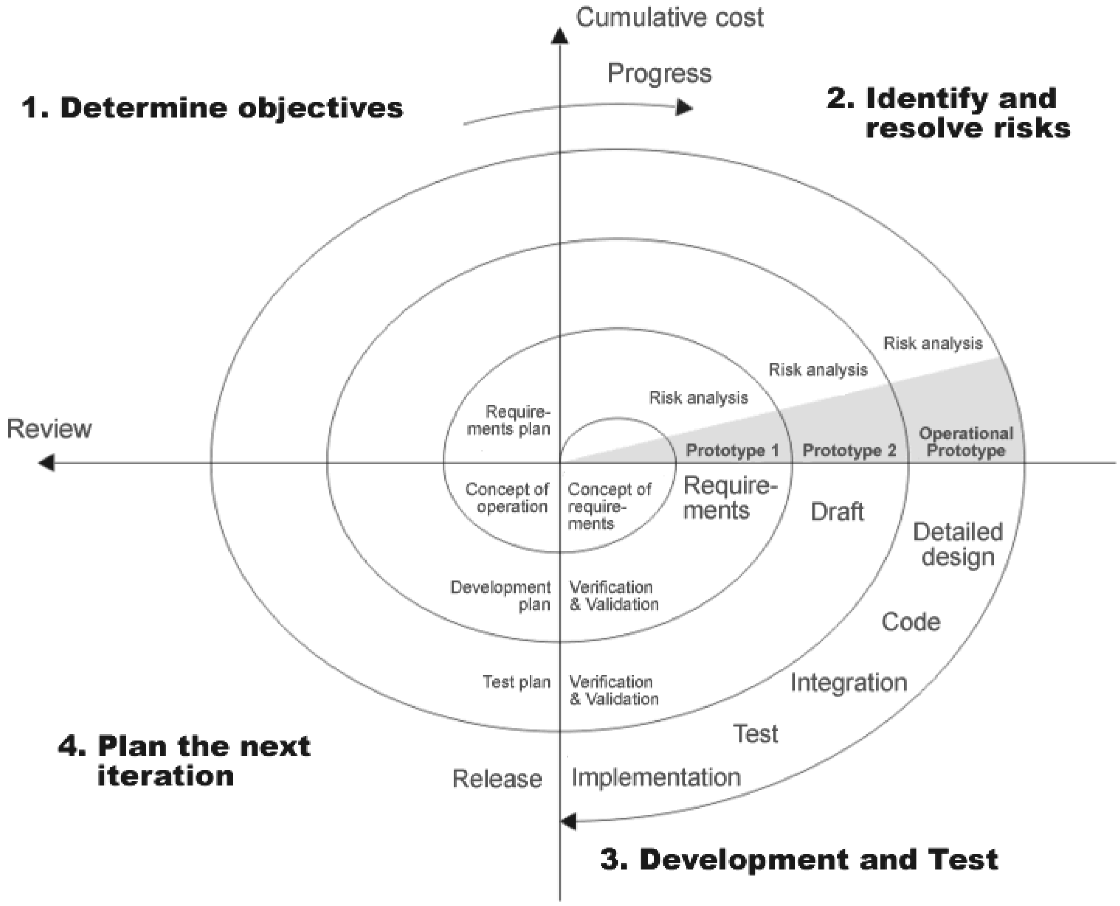

Figure 4. Spiral Development Model (source: Blanchard and Fabrycky 2011)

The systems engineering "Vee" seen in Figure 5 shows the activities that engineers perform and is a roadmap for the systems engineering process to ensure that the final product is consistent with original stakeholder needs and system requirements. The left side of the "Vee," also known as the decomposition side, begins with defining the operational need and applicable stakeholders. The decomposition and definition process, seen as an arrow proceeding down the left side of the "Vee," is the progression from the "operational need to the system-level requirements" and the "specifications" for each component. The "Vee" is "iterative" in all aspects of the "design process, from high-level issues such as stakeholder requirements to low-level issues such as component design." This is "accomplished by moving vertically in the Vee over short increments of time" within the 'Vee.' The "right-hand side of the 'Vee'" typically contains activities

involving the "assembly of lower level components into higher level components, and the assembly of high-level components into the system." For the purposes of this project the "right-hand side of the 'Vee'" was used for verification and validation activities as seen in Figure 6 and Figure 7 (Buede 2011).

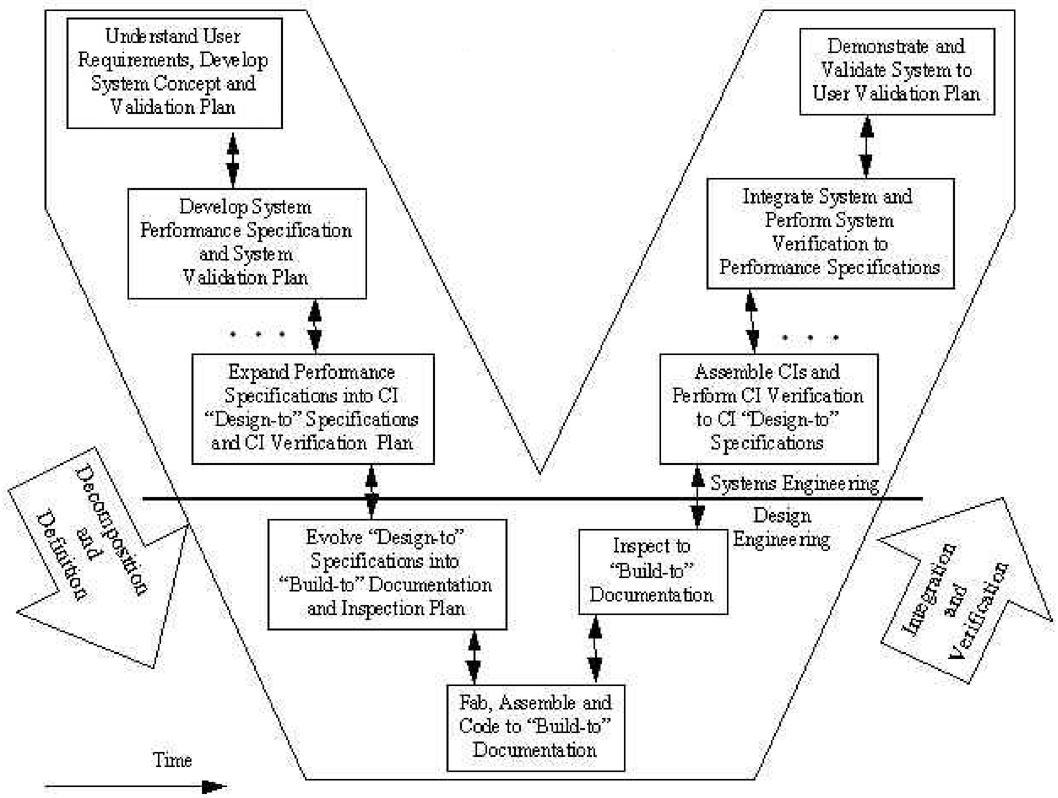

Figure 5. Systems Engineering "Vee" (source: Blanchard and Fabrycky 2011)

2. Tailored Approach

The tailored systems engineering approach used consists of a modified traditional systems engineering "Vee" model that ensured all stakeholder inputs, needs, and requirements were included in the final project solution. The overall continuity of the systems engineering process is shown in Figure 6. This view displays the engineering work conducted (or to be conducted) over previous, current, and probable future MIW projects. The diagram has been nicknamed the "telephone cord Vee" and its purpose is to show that the previous MIW team (2014) completed its entire iteration of the systems

engineering process in fulfillment of their project objectives prior to providing the configuration recommendation to the current MIW team (2015) as the input or starting place for the MIW 2015 project specific systems engineering process. The systems engineering continuity approach shows the iterative process through each individual project. Each iteration does not necessarily use the outputs from the previous project for the inputs to the follow-on project. The continuity method intends to show the previously completed systems engineering (SE) "Vee" while showing the progression of the SE process through the various iterations of each project. System verification and validation consist of model functionality verification and validation activities with respect to system requirements and stakeholder needs. Each iterative "Vee" provides a recommended configuration as an output for the next project's system engineering process input.

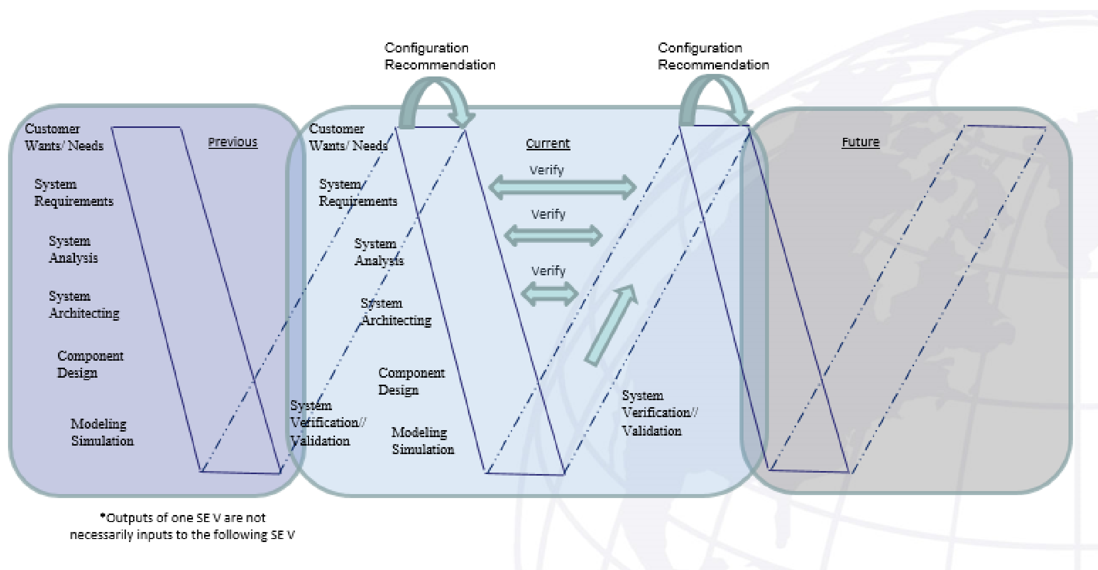

Figure 6. Overview of SE "Vee" Continuity

This current project followed a tailored SE process, using some of the recommended configuration outputs from the previous group, but tailoring the majority of the project based upon updated stakeholder inputs and needs. Figure 7 shows the tailored engineering process that begins with the configuration recommendations received as the output of the previous MIW 2014 process and proceeds through the right hand side activities of the SE "Vee" to include stakeholder analysis and need input,

system requirement development, system analysis and architecting, component design, and finally modeling and simulation. The right-hand side activities of the SE "Vee" consisted of the verification and validation of the activities on the left-hand side of the SE "Vee." The output is a stand-alone model that satisfies stakeholder's requirements and that can be used to evaluate a current MCM problem. The output, or solution of the "Vee," will also include a recommendation for potential follow-up work to be conducted by a future Capstone team who will use some, all, or none of the recommendations based upon their tasking and stakeholder inputs.

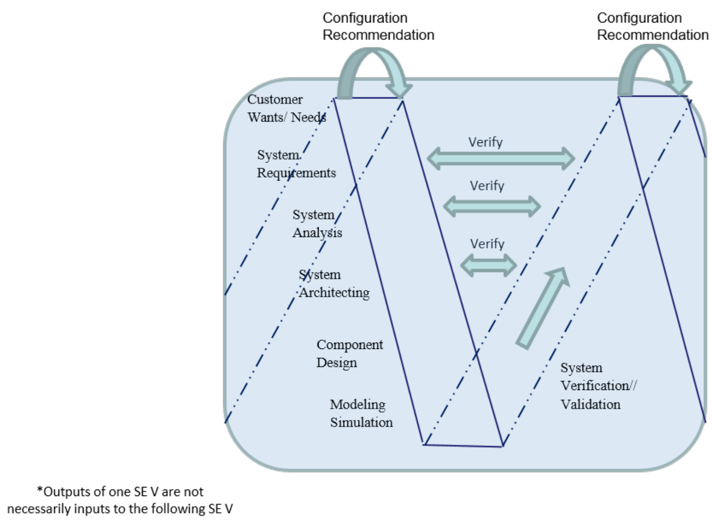

Figure 7. Tailored SE "Vee"

In the first activity, stakeholder wants and needs were obtained through research, stakeholder inputs, and stakeholder provided system requirements. This information determined the basis for the SE process and ultimately the output at the other end of the SE "Vee." These stakeholder requirements along with other systems engineering analysis results (operational concept, input output models, context analysis, and functional analysis) were translated into the top level system requirements. Systems architecting used the wants, needs, and requirements to create a high-level system design satisfying stakeholder requirements. Component design consisted of the modification of the individual model elements that existed in the original model as well as any additional

elements that were added to bring about the additional capability, as determined in the systems architecting phase, to meet the requirements determined during the systems requirements phase. Modeling and simulation with known data points was performed to ensure that a successfully modified model, codenamed the autonomous remote mine-hunting simulation (ARMS) model, existed and functioned according to the system requirements. Activities on the right-hand side of the "Vee" consisted of the verification and validation of model functionality and ensuring that the outputs were consistent with all left-hand SE "Vee" activities. This included model "runs for record" to satisfy project data collection purposes, any possible excursions that arose during the execution of this project, and the configuration recommendation for potential future project work.

The specific activities listed above are detailed within this chapter and is illustrated in Figure 8. The below terminology referring to systems engineering activities is used to be consistent with that used in the previous MIW project deliverables to include the project report, but map to the terms used in the tailored SE "Vee" above. Requirements analysis equates to "system requirements," functional analysis is used in place of "system analysis" and "system architecting," physical synthesis captures "component design."

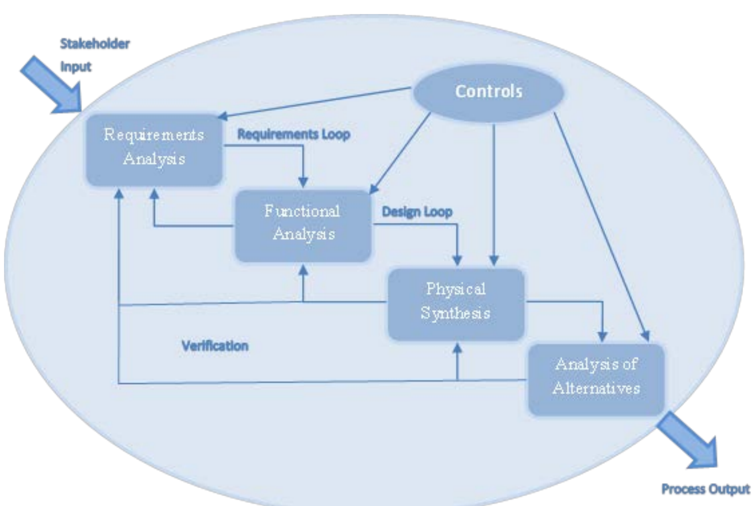

Figure 8. Application of Tailored SE Process (adapted from Frank et al. 2014)

The systems engineering approach for this iteration of the MIW project largely followed and mirrored the previous approach that was used by the previous MCM team, but was tailored to address the iterative nature of this project, not only within the project specific SE "Vee" but also within the overall continuity of SE "Vees."

B. REQUIREMENTS ANALYSIS

The tailored SE process began with the receipt of stakeholder input which flowed into the requirements analysis phase as illustrated in Figure 9. The requirements analysis phase consisted of performing a stakeholder analysis that would define the initial need and form a problem statement. Stakeholder input was combined with existing capabilities, as well as proposed capabilities, to develop requirements based off of stakeholder input, stakeholder analysis, and relevant literature reviews and SME feedback.

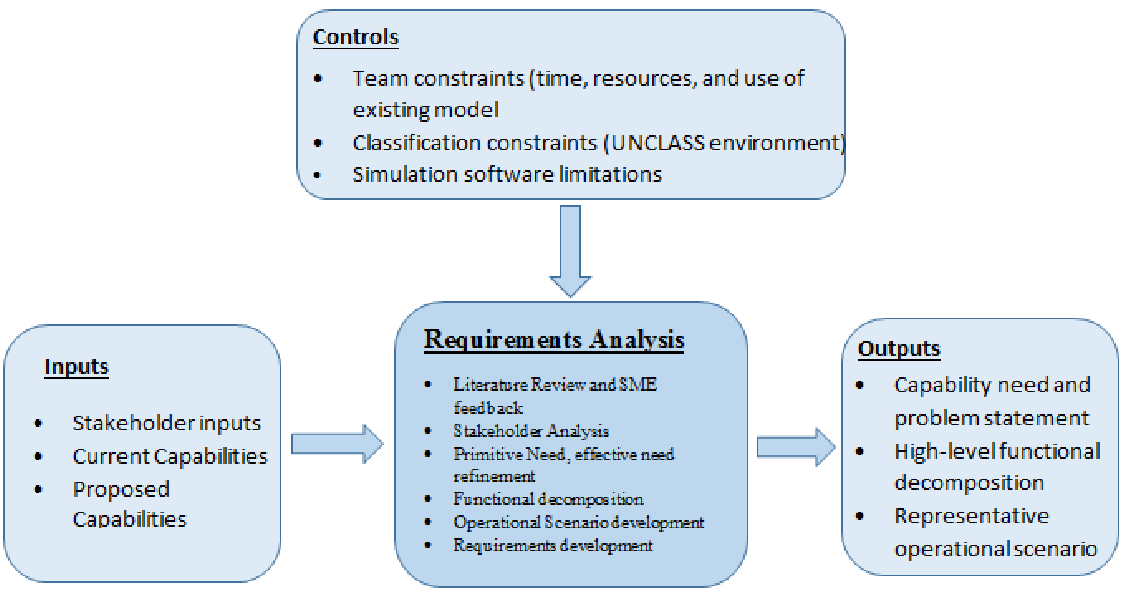

Figure 9. Requirements Analysis (adapted from Frank et al. 2014)

During stakeholder analysis the team received feedback from various MIW subject matter experts which allowed for the refinement of the primitive needs statement into an effective needs statement. Functional decomposition and the development of operational scenarios flowed into the development of relevant functional requirements.

Once the high-level functional requirements were formed a capability needs statement, problem statement, high-level functional decomposition, and a representative operational scenario were output to the functional analysis block.

C. FUNCTIONAL ANALYSIS

Functional analysis consisted of functional decomposition of the existing model inherited from the previous MIW team in order to understand it. This included the need for a deep understanding of how variables and other values were passed from block to block within the model. This information was necessary to determine a path forward that would lead to the successful implementation of proposed model modifications.

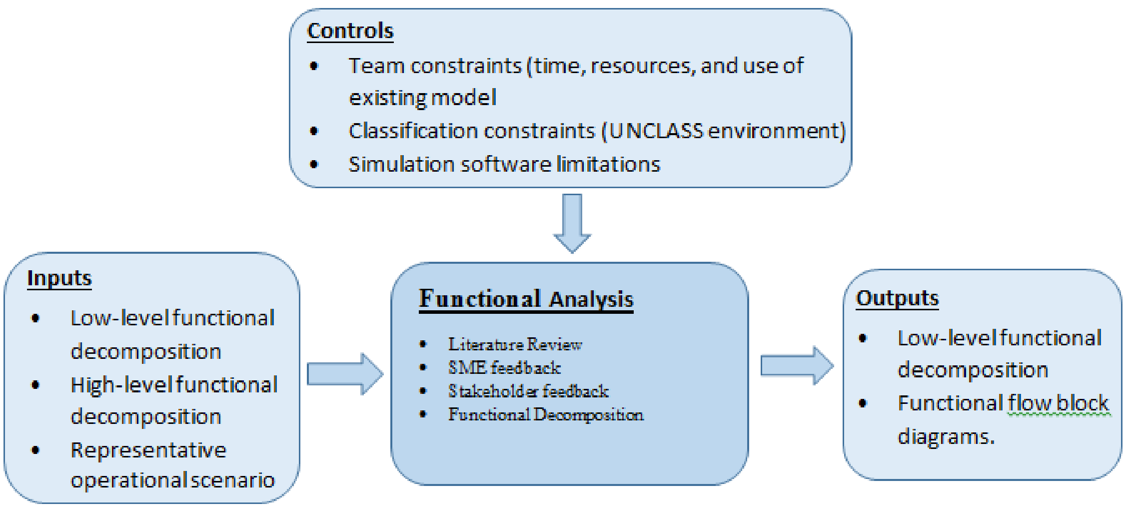

Figure 10. Functional Analysis (adapted from Frank et al. 2014)

To better understand how the model was constructed, and to understand how the model should function to meet stakeholder requirements, discussions about the model were held with the primary modeling SME from the previous MIW team as well as other MIW SMEs to include those directly involved with the MK18 Mod 2 system. This allowed the team to better understand the many processes necessary to successfully conduct the comparative analysis study per stakeholder requirements and within the context of the existing model. Outputs of functional analysis were used as inputs to the physical synthesis block. These outputs consisted of low-level functional decomposition

and functional flow block diagrams (FFBDs) as well as the planned modifications to the existing model in order to satisfy project goals.

D. PHYSICAL SYNTHESIS

Planned modifications to the existing model were performed during the physical synthesis phase. Detailed in Figure 11, this phase used the low-level functional decomposition, operational scenarios, and the developed functional flow block diagrams from the functional analysis phase as inputs. The physical synthesis phase consisted of additional SME and stakeholder feedback as well as the implementation of proposed model modifications.

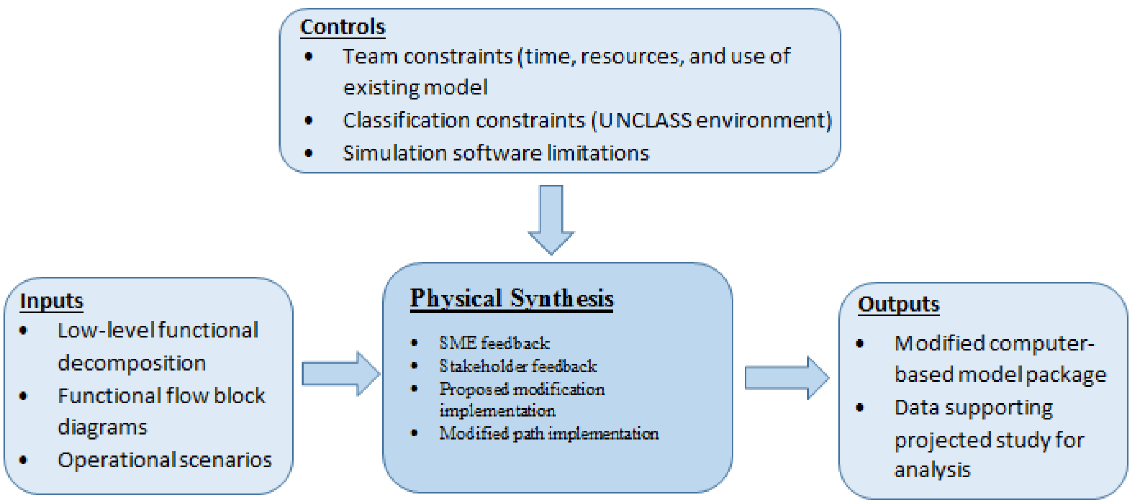

Figure 11. Physical Synthesis (adapted from Frank et al. 2014)

Limitations in the modeling software as well as limits in the existing model slowed the advance of this phase of the project. The scope of the project was evaluated and simplified to facilitate model modification utilizing two, instead of four, MK18 Mod 2 search assets. The limitations persisted even after this reduction in scope. With these limitations in mind a modification to the forward path was developed and proposed to project leadership. The proposed modification allowed for the projection of data collected from a functioning version of the model to be used to provide simulated results that would far exceed any data provided by any working version of the model, with either two

or four MK18 Mod 2 search assets. The output of the physical synthesis processes were a complete, ARMS model that produced resultant data utilized within the comparative analysis portion of the project.

E. ANALYSIS OF ALTERNATIVES

Outputs from physical synthesis were the input into the analysis of alternatives to support the required analysis of provided performance data and simulation output data. The ARMS model was used to perform the modeling simulation "runs for record" based off the previously performed design of experiments. With this data the team performed the performance and cost comparisons of interest to project stakeholders.

During the progression of the project an analysis of alternatives (AoA) was conducted to compare the modeling and evaluation approaches to be implemented during the study. The team was provided an ExtendSim model as the baseline for study extension. Multiple modification methods and approaches were compared by the team prior to implementation of the chosen course of action (COA). Using the approach modeled in Figure 12, the analysis COA options were identified and evaluated for consideration for use within the study.

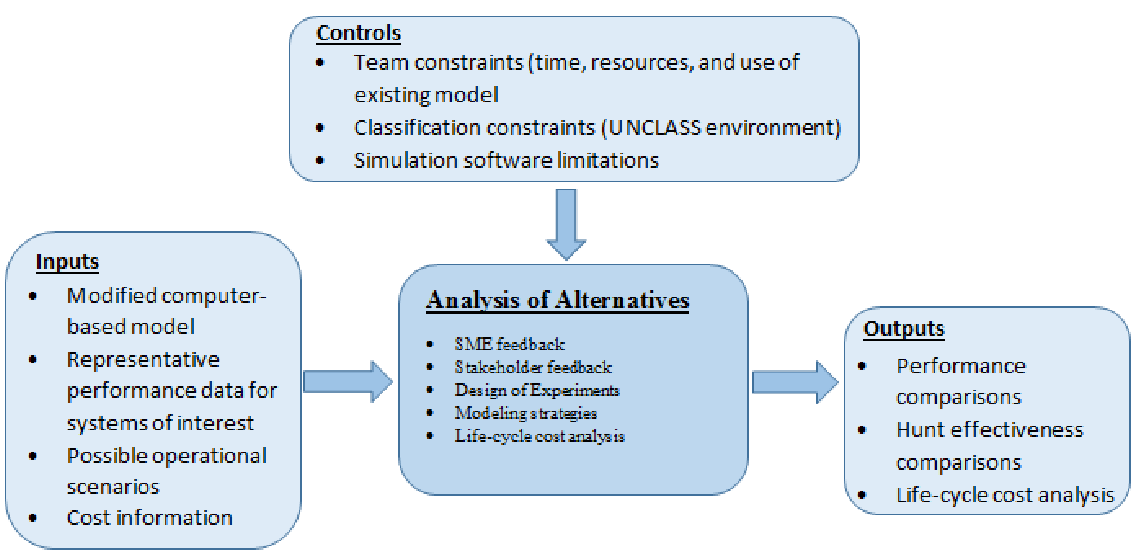

Figure 12. Analysis of Alternatives (adapted from Frank et al. 2014)

Inputs to the analysis included the provided computer based model and the performance parameters of the systems being evaluated in particular the key MOE/MOP of ACRS and percent clearance. The controlling factors of the analysis were the time available to complete the study in the allotted capstone period, the limitations imposed by utilizing an existing model and having only generalized unclassified data. Outputs of the analysis provide a comparison of the overall hunt and mission effectiveness including cost and risk factors. Preparation for the analysis included collecting data and information from stakeholders and that was derived during the literature review, expanding upon this knowledge to create a design of experiment (DOE) for evaluating the model strategies to predict the operational effectiveness. Performance of the overall analysis then included the implementation of the selected COA and generated sample data to produce the resultant recommendation. Through the application of a rigorous approach to engineering problem-solving the team worked to employ a DOE scenario that operated in a systematic manner. The team applied these "principles and techniques at the data collection stage so as to ensure the generation of valid, defensible, and supportable engineering conclusions" (NIST 2013, 1) presented in this report.

F. MODELING METHODOLOGY

As described above, an AoA was performed to compare the methods available for use in assessing the current RMS versus the MK18 Mod 2 system. The results of simulating an RMS and the MK18 Mod 2 system were compared against identical minefields. In the case for the MK18 Mod 2, it was simulated and compared to the RMS with 11 different combinations. The combinations of MK18 Mod 2s are described in Table 1. For example, the first combination consisted of a single MK18 Mod 2 released into the minefield from a single rigid hulled inflatable boat (RHIB). The second combination consisted of two MK18 Mod 2s hunting and detecting mines simultaneously launched from a single RHIB. The third combination consisted of three MK18 Mod 2s hunting and detecting mines simultaneously launched from two separate RHIBs. The output metrics from the simulations were analyzed to see which platforms were able to fulfill the requirements of the study. Since the 2014 MIW team championed ExtendSim over map aware non-uniform automata (MANA) through their AoA, the 2015 MIW team

continued to utilize ExtendSim to simulate the RMS and MK18 Mod 2 configurations. A description of ExtendSim is included in Chapter VI and the evaluation is extended in Appendix A.

Table 1. MK18 Mod 2 Combinations

Configuration	Platform	Transportation
1 UUV	MK18 Mod 2	1 RHIB launched from LCS
2 UUVs	MK18 Mod 2	1 RHIB launched from LCS
3 UUVs	MK18 Mod 2	2 RHIBs launched from LCS
4 UUVs	MK18 Mod 2	2 RHIBs launched from LCS
5 UUVs	MK18 Mod 2	3 RHIBs launched from LCS
6 UUVs	MK18 Mod 2	3 RHIBs launched from LCS
7 UUVs	MK18 Mod 2	4 RHIBs launched from LCS
8 UUVs	MK18 Mod 2	4 RHIBs launched from LCS
9 UUVs	MK18 Mod 2	5 RHIBs launched from LCS
10 UUVs	MK18 Mod 2	5 RHIBs launched from LCS
12 UUVs	MK18 Mod 2	6 RHIBs launched from LCS

Of concern was the ability of the model to accommodate the addition of multiple search vehicles operating in parallel and alternative means within the project constraints while producing meaningful data and determining the proper approach to accomplish that goal. The team initially performed limited reverse engineering of the software modules comprising the model to identify areas for which the model could be extended to support the current and potentially future studies of MIW. Using the gathered information several COAs were developed and an analysis of the alternative approaches was conducted to

determine the appropriate methodology, followed by implementation of select code changes and simulation runs for evaluation of suitability prior to committing the model code changes. Alternatives were measured against criteria and selected or rejected for further development until a single modeling approach was selected.

During the evaluation two differing approaches were initially developed into multiple working models for evaluation over the course of several weeks. Through the use of controlled input data to calibrate the model, runs were completed for comparison of key MOEs to the baseline model. The results of these calibration runs exposed additional issues that were traced over multiple model iterations to the arrival time of the identified mine-like contact (MILCO) into the post mission analysis (PMA) portion of both models. Further modification of the models to batch the MILCO was implemented and evaluated by the team while other strategies were developed in accordance with the previously listed criteria. It was determined that although the models produced expected values for the critical MOE of number of mines neutralized, achieving the result was due to the implementation of artificial delays in the model which would not be present in an operational scenario. Due to this finding one of the model approaches was determined no longer to be a feasible approach and was abandoned in favor of re-writing the PMA code as the long term solution for use in continued studies. In conjunction with the recoding efforts and discussions with NMAWC MIW requirements N8 Richard Kimmel, an alternative approach to producing meaningful data was determined (Richard Kimmel, personal comm.) which would focus on the effectiveness of the hunt portion of the MK18 to the RMS and legacy systems for comparison using the results of a single hunt asset. The approach was deemed as acceptable by the stakeholders because the airborne neutralization assets were of known performance characteristics and consistent among the comparative systems. Of primary interest was the determination of the number of MK18s which meet and/or exceed the hunt effectiveness of the RMS and legacy configurations and associated costs to allow for a safer search mission by removing the human from the mine field (Richard Kimmel, personal comm.).

G. CHAPTER SUMMARY

There exists many different methods and models detailing the systems engineering process. Waterfall, spiral, and the systems engineering "Vee" models all have benefits as well as drawbacks. The waterfall model, being somewhat restrictive, was not chosen for use in this project. The spiral model was intended to fix the inflexibility of the waterfall model through the development of multiple prototypes throughout each phase iteration. Due to time restrictions and deliverable requirements this model was not chosen. The systems engineering "Vee" model came the closest to satisfying the project needs but was still required slight modification to address all aspects of this project. Of the many models that are available to the systems engineer, there is not always a model in existence that meets the needs of every project. Such was the case for this project. While the typical SE "Vee" model was somewhat sufficient, it did not meet all the requirements necessary. The need to show project continuity and carryover was required to correctly characterize the process utilized. To correct this, it was determined that using a modified SE "Vee" model in an iterative fashion, similar to that of the spiral model (essentially placing iterative SE "Vees" in a row) would satisfy project objectives. This method allowed for the current iteration of the MIW project (MIW 2015) to accept recommendations from the previous MIW team (2014), proceed through its own SE "Vee" and provide recommendations to a future MIW team.

The systems engineering activities of requirements analysis, functional analysis, physical synthesis, and analysis of alternatives were conducted as part of the systems engineering process and mirrored that of the previous MIW project (2014). These activities identified relevant stakeholders to identify the primitive need develop a need and problem statement. From this problem statement, a functional decomposition was conducted in the functional analysis phase. In the physical synthesis phase, relevant stakeholder and SME feedback was taken and proposed modified path forward was identified and executed. Analysis of alternatives (AoA) conducted a design of experiments from which data was generated for analysis. A life-cycle cost (LCC) analysis was also performed in this phase to compare hunt effectiveness with the most cost

effective configuration. Of importance during the AoA phase was the need to develop a modified method for getting the data require for analysis.

III. REQUIREMENTS ANALYSIS

In conjunction with the literature review and analysis of the 2014 MIW model, the team conducted additional research of operational and developmental activities in order to develop the preliminary problem definition and scope for the ARMS model. Through further study and feedback from the core MIW SMEs and advisors, a set of primitive needs was developed and further refined into an effective needs statement. The MIW team's process continued to evolve the effective needs into a detailed problem statement, in line with the project's technical and time constraints to scope the effort accordingly.

The content of this chapter details the processes used to recognize relevant roles of the primary and secondary MIW stakeholders, then identify, analyze, prioritize and transform their collective primitive needs into a common effective need. The process is further detailed in the methods the team used to transform the stakeholder's recognized mission capability need and effective need under the project's constraints into a concise problem statement bounding the study's scope.

A. STAKEHOLDER IDENTIFICATION AND ANALYSIS

Since this project built upon the previous work of the NPS MIW Team 2014, a limited stakeholder identification process was implemented. The performance of a stakeholder analysis ensures that the needs of all stakeholders are given suitable consideration in relation to influence, impact or importance during the performance of the SE process. This project's additional stakeholders, combined with those previously identified, were those entities discovered during the research of the LCS MIW MP as a replacement of the MCM and the potential inclusion of the MK18 Mod 2 as a supplement or replacement of aspects of that MP.

As stakeholders' needs drive system requirements and ultimately design, all reasonable attempts to identify and capture the desires of the stakeholders during the analysis process were made to allow for the accurate description of the problem area bounded by the project constraints. The following steps adapted from the International

Council on Systems Engineering (INCOSE) processes were performed in the execution of the stakeholder analysis as follows:

1. Identify potential stakeholders and their interests in MIW, LCS MP and the MK18 Mod 2.
2. Classify the potential stakeholders in accordance to impact and influence.
3. Determine and rank first and second order stakeholder priorities.
4. Identify the primitive needs of the stakeholders.
5. Analyze the collective primitive needs and determine the effective need.
6. Transform the effective need into requirements and a preliminary problem statement.
7. Provide the preliminary problem statement to stakeholders and advisors for concurrence and feedback (iterated as necessary to refine statement).
8. Include stakeholder feedback into formalized requirements.

The initial list of stakeholders for this project was inherited from the NPS MIW Team 2014 project and expanded by the MIW Team 2015 to include those associated or interested with the development, deployment and sustainment of the MK18 Mod 2. Research into the stakeholder's involvement of MIW and the MK18 Mod 2 and feedback from other stakeholders resulted in an adjusted list of stakeholders, with the classification or prioritization of some stakeholders becoming less influential. This re-ordering occurred through evaluation of the stakeholder's level of interaction with MIW as performed by the LCS or the MK18 Mod 2, and categorized as; internal, first-order or second-order. An internal stakeholder is classified as an entity whose interaction with the LCS MIW or MK18 Mod 2 systems is direct. Those stakeholders determined to have interactions with the LCS MIW or MK18 Mod 2 mission, but not direct interaction with the system are classified as first-order. Stakeholders whom have no direct interaction with the system or mission except through first-order stakeholders have been classified as second-order. The first-order and second-order stakeholders comprise the boundary stakeholders. After the internally and boundary stakeholders were classified, the relationships between the stakeholders and the MCM systems were analyzed (Frank et al. 2014).

The ranking and prioritization of the stakeholders allows for the determination of critical system parameters by the SE team. In order to perform the prioritization of the stakeholders, the level of influence on the life cycle cost and operational needs of the

system is considered which aids in resolving conflicts of needs if required. In the design of a system, stakeholder prioritization is a key attribute in determining those elements which shape the development of the architecture, acquisition strategy and operation of the system (INCOSE 2010). Once identified as a key stakeholder they were categorized as primary or secondary with the needs of the primary stakeholders requiring satisfaction and those of the secondary satisfied as possible. The primitive needs of the stakeholders were discussed, MOEs analyzed, and evaluated by the MIW 2015 team and stakeholders to refine and produce the resultant effective needs and problem statements for this research.

The stakeholder's needs, as expressed in the problem statement, allowed for the team to develop and derive the project requirements in accordance with the previously determined scope. The established requirements allowed for the study of current MCM capabilities to be adequately measured against modeled future capabilities to satisfy the needs of the MIW community. The MIW community is comprised of both primary and secondary stakeholders, dependent upon both their interactions within the MIW community and involvement with this project. The listing of stakeholders, their categorization and description of MIW or project involvement is detailed in Table 2 adapted from the MIW 2014 report.

Table 2. Stakeholder Identification and Analysis (adapted from Frank et al. 2014)

Stakeholders	Classification (Project, Internal, 1st, 2nd, Boundary)	Type Prioritization (Primary, Secondary)	Level of Involvement in MIW	Interest in MIW & MCM (Primitive Need)
N95 (Expeditionary Warfare)	1st Order	Primary	Responsible for assessing requirements for naval expeditionary warfare missions and programs, including MIW. Also responsible for determining characteristics and structure for all MIW ships. ("[Office of the Chief of Naval Operations] OPNAV 95" 2013)	Interested in capabilities assessments and recommendations for enhancements to shipboard, deployable vehicles. Particularly interested in assessments that help prioritize future system acquisition based on total capability delivered vs. cost.
Naval Mine and Anti-Submarine Warfare Command (NMAWC)	1st Order	Primary	Develops doctrine and TTPs. Articulates the ASW operational and future readiness, capabilities and requirements. Supports ASW performance assessments at all level against standardized, common metrics (ASW, 2015)	Interested in the performance of emerging MIW capabilities as stated in personal meeting 3 August 2015. Of particular interest were the number of MK18 Mod 2 devices required to equal the effective ACRS of current MCM operations.
NSWC PC	Internal	Primary	Conduct research, development, test and evaluation (T&E), in-service support of MIW systems, mines, naval special warfare systems, and other systems primarily occurring in coastal regions. (Naval Sea Systems Command n.d.—b)	Interested in all aspects of MIW. As stated in 9 May 2014 meeting and in personal communication dated 15 May 2014, particularly interested in increasing the ACRS for defensive MCM operations.
NSWC, Future Ship Concept Branch	Internal	Primary	Specializes in ship design & integration. (Naval Sea Systems Command, n.d.—c)	Interested in requirements for ship designs and equipment integration that enable best performance of MIW operations.

Stakeholders	Classification (Project, Internal, 1st, 2nd, Boundary)	Type Prioritization (Primary, Secondary)	Level of Involvement in MIW	Interest in MIW & MCM (Primitive Need)
PEO LCS (Formerly PEO LMW)	Internal	Primary	Responsible for acquiring and maintaining the littoral mission capabilities of the LCS class including programs to support MIW (Secretary of the Navy n.d.)	Interested in capabilities assessments and recommendations for enhancements to shipboard, deployable vehicles
PEO Ships	Internal	Primary	Responsible for executing the development and procurement of all destroyers, amphibious ships, special mission and support ships, and special warfare craft. (Naval Sea Systems Command n.d.—d)	Interested in capabilities assessments and recommendations for enhancements to shipboard, deployable vehicles
NPS	Project	Primary	Conducting research and development to support the warfighter. Provide quality educational environment to prospective SEs for DOD.	Interested in developing new strategies and system for MIW Operations. Interested in developing skilled DOD SE personnel.
Admiral Richard Williams III (Ret.)	Project	Primary	Primary MIW expert consultant for NPS led study.	Interested in providing expert advice for the MIW Team to ensure the development of quality, useful research-based product.
SSC PAC MK18 Mod 2 program support	1st Order	Secondary	Responsible for MK18 system development in order to meet N95 requirements.	Interested in developing capability to meet emerging requirements. Developing new technologies to further capabilities based on stakeholder desires.
Personnel: Navy and Marines	Internal	Secondary	Operational involvement	Interested in the best equipment and methods to destroy enemy sea mines.
PMS 340: Naval Special Warfare Program Office	Internal	Secondary	Involved in the development of systems and procedures for naval special warfare operations.	Interested in outfitting the War Fighters with the best equipment and training possible to accomplish the mission.

Stakeholders	Classification (Project, Internal, 1st, 2nd, Boundary)	Type Prioritization (Primary, Secondary)	Level of Involvement in MIW	Interest in MIW & MCM (Primitive Need)
PMS 403: Remote Mine Hunting Program Office	Internal	Secondary	Involved in the development of systems and procedures for remote mine hunting.	Interested in outfitting the War Fighters with the best equipment and training possible to accomplish the mission.
PMS 406: Unmanned Maritime Systems Program Office	Internal	Secondary	Involved in the development of systems and procedures for maritime surveillance operations.	Interested in outfitting the War Fighters with the best equipment and training possible to accomplish the mission.
PMS 420: LCS Mission Modules Program Office	Internal	Secondary	Involved in the development of systems and procedures for LCS Mission Module Systems.	Interested in outfitting the War Fighters with the best equipment and training possible to accomplish the mission.
PMS 495: MIW Systems	Internal	Secondary	Involved in the development, fielding, and –n-service support for all mining and mine countermeasure systems in the areas of mine hunting, minesweeping, mine neutralization, and the development of mines for offensive MIW. (PMS 495 Mine Warfare Program Office 2008)	Interested in developing the highest value MIW systems possible.
Nation's Allies	Boundary	Secondary	Direct stakeholders as mines can affect any allied nation with littoral coastline.	Interested in protecting their naval and commercial shipping, and keeping their SLOCs open.
PMS 480: Anti-Terrorism Force Protection Afloat Program Office	Boundary	Secondary	Involved in the development of systems and procedures for maritime anti-terrorism operations.	Interested in outfitting the War Fighters with the best equipment and training possible to accomplish the mission.
PMS 485: Maritime Surveillance Systems Program Office	Boundary	Secondary	Involved in the development of systems and procedures for maritime surveillance operations.	Interested in outfitting the War Fighters with the best equipment and training possible to accomplish the mission.

Stakeholders	Classification (Project, Internal, 1st, 2nd, Boundary)	Type Prioritization (Primary, Secondary)	Level of Involvement in MIW	Interest in MIW & MCM (Primitive Need)
N81 (Assessments)	1st Order	Secondary	Involved with the determination of system effectiveness through the conduct of capability assessment analyses for war fighting and war fighting support. Also responsible for the integration and prioritization of enhancements and upgrades to capabilities. Lastly, interested in the development and validation of analytic tools and techniques. ("N81 Alignment Warfare" 2006)	Interested in methods to enhance and/or upgrade existing MIW scenario and war fighting models
N96 (Surface Warfare)	1st Order	Secondary	Responsible for determining requirements for surface combatants and support ships, as well as to coordinate, supervise, and execute Navy shipbuilding for above surface combatant ships. ("OPNAV N96" 2013)	Interested in developing improvement modifications to the LCS current design

Table 2 (continued)

B. PROBLEM DEFINITION

Stakeholder desires were analyzed in order to develop the primitive need. The primitive need is the need stated by the stakeholders and is often their perception of what is needed to solve a perceived problem. While the primitive need *may* encompass the eventual solution, more analysis is necessary to determine the correct path forward. The first step in analyzing stakeholders' actual problem is the development of the effective need. The effective need is a broader statement of needs that should identify what the stakeholder really wants that solves the actual problem. The capability need statement

defines the capability needed in order to solve the stakeholders' problem. Finally, the problem statement defines the real, overarching problem, based on research into stakeholders' primitive needs that requires solution.

1. Primitive Need Summary

During the weekly meetings of Team MIW 2015 and their capstone advisors, various stakeholders, including RDML (Ret.) Rick Williams, expressed the desire to compare the MK18 Mod 2 mine detection system to the LCS MCM RMS mine detection system in order determine potential methods of increasing the LCS MCM capability. The main purpose of this comparison was not only to determine the most effective methods of utilizations, but in order to determine which capabilities provide the best value. The MIW community wants to compare the developmental MK18 Mod 2, and other autonomous mine detection systems to the RMS used in the LCS MCM Mission Package in order to determine relative effectiveness and recommended methods of use for effective and efficient mine detection and elimination and inform future force structure decisions.

2. Effective Need Summary

Based on the results of the literature review and stakeholder analysis, the primitive need was refined to the effective need. The U.S. Navy and its allies continue to study and develop new capabilities in order to more effectively combat mines laid by an array of enemy forces. A major focus of this has been the removal of warships and humans from the actual mined space (Program Executive Office Littoral and Mine Warfare 2009). In doing so, the U.S. Navy and its allies have expressed difficulty in comparing legacy MCM 1 capabilities with the new capabilities provided by the LCS MCM Mission Package and other emerging technologies (Frank et al. 2014). The U.S. Navy needs to have this comparison capability in order to ensure that new and future capabilities provide effects as good as or better than the legacy capabilities for equal or lower cost.

3. Capability Need Statement

The U.S. Navy and its coalition partners need the ability to compare advanced and evolving Mine Warfare capabilities to baseline as well as against legacy MIW capabilities in terms of merit and value. This includes programmatic, operational and budgetary considerations.

4. Problem Statement

The MCM 1 Avenger class vessels are planned to be completely retired by 2024 (Program Executive Office Littoral and Mine Warfare 2009). The LCS MCM MP is the intended successor and will overlap the legacy systems. The graphical depiction in Figure 13 is intended to be representative of this overlap, but it is not known at this time what the real overlap will be, as delays in development and acquisition continue to push back initial operating capability (IOC) of the LCS MCM MP (United States Government Accountability Office 2014). In addition, it is unknown what total capability will be available to conduct mine warfare with the LCS MCM MP, how to employ it, how it compares to existing capability, which envisioned elements provide the best value, or what the final cost will be. The MIW community needs to develop a comprehensive comparative solution to clearly define the gaps between legacy, future, and projected MCM capabilities while providing recommendations involving effectiveness and value for the conduct of sound tradeoff decisions.

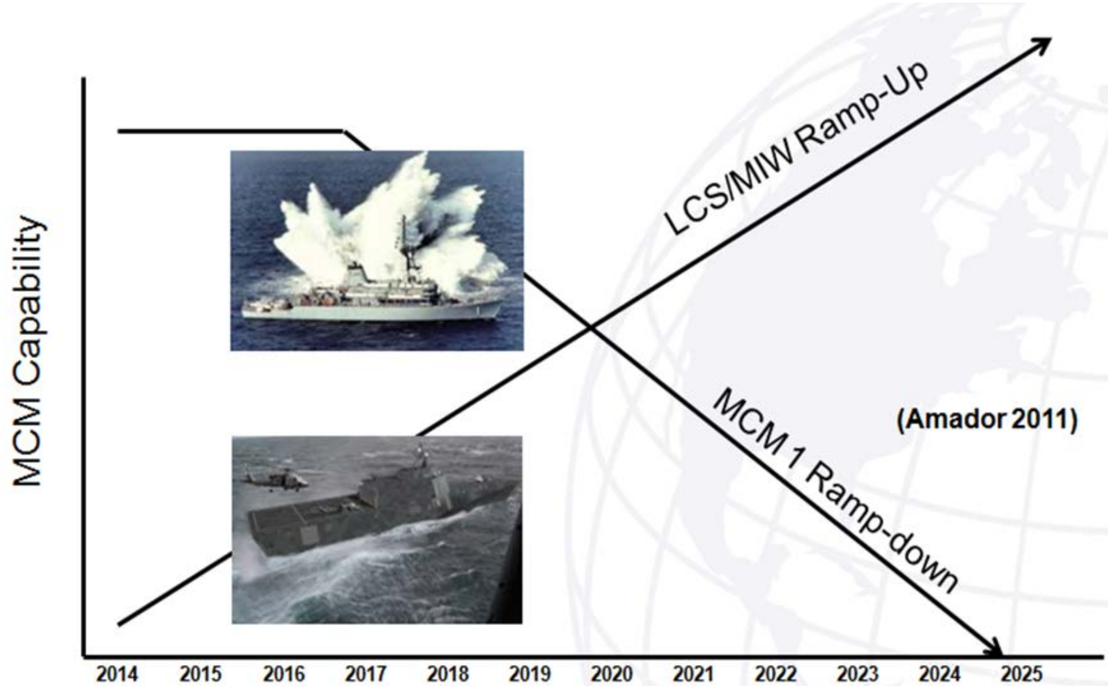

Figure 13. Notional Legacy and Future System Overlap

C. OPERATIONAL SCENARIO

The operational scenario is discussed in detail within Chapter IV.

D. REQUIREMENTS

Requirements are the statements used "to set up the standards and measurement tools for judging the success of the system" (Buede 2011, 153). In essence, this is the distillation of stakeholder mission needs into clear statements that can be used to formulate the specific design of the system. Requirements are hierarchical in nature, with the highest level of requirements being mission based and the lowest level intended for detailed design work of individual configuration items (Buede 2011).

A goal of the MIW Team 2014 and 2015 Capstone teams was to design and build a model for simulation in order to fulfill stakeholder needs. The goal of the MIW Team 2015 requirements process was to develop the high level requirements needed to guide model design in order to ensure they fulfilled stakeholder desires to quantitatively compare the MK18 Mod 2 to the current LCS MCM MP RMS.

The MIW 2014 Capstone group created a model that conducted simulation comparisons of the legacy MCM 1 Avenger vs. the LCS MCM MP in various configurations (Frank et al. 2014). The initial intent was to reuse this model if at all possible. To maximize the usefulness of any model extensions, the following overall requirements were stated.

R.0 The system shall simulate an operational scenario of the legacy MCM 1 Avenger and the MK18 Mod 2 in specified configurations.

- R.1 The model outputs shall be comparable to MIW Capstone 2014 outputs.
- R.2 The model shall simulate the MK18 Mod 2 parameters in place of the LCS RMS.

Requirement 1 is necessary to maintain backwards compatibility with the previous capstone conclusions. This desire was stated as a means to maximize the information that can be extracted from the combination of the two studies. Requirement 2 is the focus area for this capstone based on the stated desires of stakeholders. These two high level requirements formed the basis of the MIW 2015 Capstone team's efforts. As the first requirement is a need to maintain backward comparability, MIW 2015 Capstone group needed to incorporate the originating requirements from the MIW 2014 Capstone group. These are presented in their entirety herein.

- "R.1 An unclassified model shall be developed to determine the operational effectiveness of the LCS versus MCM capabilities
    - R.1.1 The model shall take unclassified inputs for various performance parameters for the LCS and MCM to enable sensitivity Analysis
        - R.1.1.1 The model shall use best estimates of input factors in cases when real values are unavailable
    - R.1.2 The model shall identify parameters with high predictive power (relative to other parameters)
    - R.1.3 The model shall use an operationally relevant situation as the basis of comparison, focusing on system effectiveness in a SLOC scenario
- R.2 The model shall provide quantitative estimates of overall mine clearing effectiveness
    - R.2.1 The model shall produce a metric of ACRS
    - R.2.2 The model shall produce a metric of percent clearance to evaluate the mine hunting effectiveness" (Frank et al. 2014, 56).

Taking these requirements and combining them with our own originating requirements results in the following complete list of originating requirements.

- R.1 The model outputs shall be comparable to MIW Capstone 2014 outputs.
    - R.1.1 The model shall use a SLOC 10 nautical mile (NM) X 10 NM area as the basis of its operational comparisons.
    - R.1.2 The model shall provide quantitative estimates of overall mine clearance effectiveness.
        - R.1.2.1 The model shall record the data to enable the calculation of ACRS.
        - R.1.2.2 The model shall record the data to enable the calculation of percent mine clearance.
- R.2 The model shall simulate the MK18 Mod 2 parameters in place of the LCS RMS.
    - R.2.1 An unclassified model shall be developed or modified in order to determine the operational effectiveness of the LCS MCM Inc 1 RMS versus the MK18 Mod 2.
        - R.2.1.1 The model shall take unclassified inputs for relevant performance parameters for the LCS RMS and the MK18 Mod 2.
            - R.2.1.1.1 The model shall use best estimates of input factors when real values are not available.
    - R2.2 The model shall incorporate any additional functions necessary for the operation of the MK18 Mod 2 not required by the LCS RMS in previous simulations.

Once the originating requirements were determined, these were transformed into top-level system requirements. These are the requirements that are used to design the system in order to satisfy the originating (stakeholder's) requirements (Buede 2011). For both MIW Team 2014 and 2015, the functional and physical analysis was used to generate the parameters that the model needs to describe in order to effectively model system operation (Frank et al. 2014). As the simulation was adapted from the previous capstone team, once again the system requirements were adapted from MIW Team 2014. As in their model, there are five top-level requirements developed for the model. The adapted requirements are listed in Table 3.

Table 3. Requirements (adapted from Frank et al. 2014)

Number	Requirement	Type / MOE Mapping
1.0	The simulation shall enable the determination of the ACRS for each MCM configuration in the performance of mine hunting.	Top-Level
1.1	The simulation shall represent the time required to perform each mine hunting function within the mine hunting operation: travel, detect, classify, identify, reacquire, and neutralize for each MCM configuration.	ACRS
1.2	The simulation shall provide the data to enable the calculation of ACRS.	ACRS
2.0	The simulation shall model the effectiveness of each mine hunting function.	Top-Level
2.1	The simulation shall calculate and store the effectiveness of each mine hunting function.	Percent Clearance
2.2	The simulation shall calculate and output the overall mine hunting effectiveness in terms of the number of mines cleared, number of mines remaining, and the number of non-mines that were neutralized.	Percent Clearance
3.0	The simulation shall contain models of the mine hunting sequence of events for the different configurations.	Top-Level
3.1	The simulation shall represent each of the MCM configuration's mine hunting functions: search, detect, classify, identify, reacquire, and neutralize.	ACRS and Percent Clearance
3.2	The simulation shall represent the minefield size and location for use in the effectiveness and ACRS calculations.	ACRS and Percent Clearance
3.3	The simulation shall transition the state and mine hunting results of the previous function to the subsequent function IAW PEO LMW Instruction 3370.1A.	ACRS and Percent Clearance
4.0	The simulation shall support setting and modifying the listed performance parameters without requiring modifying the simulation.	Top-Level
4.1	The simulation shall import specified input parameters without requiring modifications to the code.	Non-Functional
4.2	The simulation shall support the export of the resulting effectiveness and time-to-complete parameters to a form that can be analyzed by statistical software products such as Excel and Minitab.	Non-Functional
4.3	The simulation shall be developed in a modular method that allows for each function to be replaced.	Non-Functional

Number	Requirement	Type / MOE Mapping
5.0	The simulation shall include documentation that facilitates the use of the simulation tool by future study groups.	Top-Level Non-Functional
5.1	The simulation documentation shall include full descriptions of all changes to the code, including any new input or output parameters, code additions, deletions and subtractions.	Non-Functional

The first top level requirement, R.1, specified the project need to calculate the ACRS for every given tested configuration and all parameter inputs. This is necessary to ensure that the differing parametric inputs can be compared using the MOEs that were previously identified. R.1.1 and R.1.2 further specify what data needs to be collected in order for the simulation to provide the information necessary to calculate the ACRS. R.1.2 differs from MIW Team 2014 as the simulation does not calculate the ACRS directly. This was done later using other tools such as Microsoft Excel and Minitab as appropriate for conducting statistical analysis.

The second top level requirement, R.2, specified the need for the model to collect effectiveness data for each phase of the mine hunting operation. Once again, the lower level requirements specify exactly what is done and how it is done in order to achieve this top-level requirement. The percent effectiveness is not calculated directly by the model, but R.2.2 specifies what information needs to be output to allow for this calculation to occur during data analysis.

The third top level requirement specifies the need for the model to simulate the specific functional differences between tested configurations. In this study, the MK18 and the RMS are the specific differences being studied. Where the RMS is launched directly from the LCS and transits to the search area, the MK18 is launched from a RHIB that is launched from the LCS. These specific differences must be modeled in the simulation. The lower level functions specify further refinement on how this is done.

The fourth top level requirement specifies the need for the model to accept differing parameters in order to see how changes to these parameters effect overall

mission effectiveness. As previously stated, these simulations are not being conducted with real data as it is either classified or unavailable. Therefore, ranges of data were used to simulate likely values. Changing the simulation for each parametric permutation is labor intensive, therefore it was determined that a need existed for the simulation to accept values from either a database or spreadsheet. This allowed for the rapid variance of input parameters supporting a Design of Experiments methodology. The top level requirement is decomposed to provide further guidance on how to accomplish this task.

The fifth top level requirement specifies the need to document the model and how it works. As this is an existing model, there is already a 500 page document detailing its setup and use. Our requirement focuses this effort to documentation of changes that are made to the simulation from the original as the existing document is already very comprehensive.

E. REQUIREMENTS ANALYSIS SUMMARY

This chapter identified the stakeholders and their desires to compare the MK18 Mod 2 mine detection vehicle and the LCS MCM MP Inc 1 RMS, defined the full underlying problem and created requirements to fulfill the needs of the stakeholders. These requirements were then taken to guide the model development and modification to meet those stakeholder needs. Other necessary work that aided this effort was the identification of ACRS and percent clearance as the primary metrics defined in Chapter I for comparison, and the definition of an operational scenario within which to compare the desired assets.

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IV. OPERATIONAL CONCEPT AND SCENARIO ANALYSIS

The U.S. Navy, as necessitated by Strategic, Joint, and Navy guidance, provides six core capabilities in order to support National Security objectives. These are forward presence, deterrence, sea control, power projection, maritime security, and humanitarian assistance/disaster relief (HA/DR) (U.S. Navy 2010). The U.S. Navy requires a robust MCM capability in order to ensure access to provide these capabilities. This chapter discusses the operational concepts and scenarios used to develop the model and simulation.

A. OPERATIONAL CONTEXT

1. Operating Area

Around 90% of the world's trade moves by sea (Department of the Navy 2015). About a third of world trade moves through the Straits of Malacca, while one-half of all oil moves through it (Evers and Gerke 2006). A third more oil moves through the Straits of Hormuz than the Straits of Malacca (Evers and Gerke 2006). A defining point of trade choke points is geography. These are locations that provide a transit path from one part of the world to another that is along the shortest route, or, as in the case of the Straits of Hormuz, the only route. These straits generally consist of largely deeper water (200 feet or greater) with a mile or more of navigable water at the narrowest point. Much of the straits are significantly wider. Any action by a state or non-state actor to threaten these choke points could have devastating effects on the world economy. The utilization of mines would be particularly threatening, difficult to detect, and damaging to international trade and global confidence.

In considering the greatest and most time consuming mine threat U.S. MCM forces could face, MCM experts presented a scenario in which a 10 x 10 NM grid, centered directly on the shipping channel, was suspected of containing mines and needed to be cleared. In order to provide an unbiased comparison, water depth was assumed to be 200 feet or greater, and only bottom mines were considered as this was the mine type most consistently comparable across the various configurations. Bottom mines are

generally effective to depths of 200 feet, and this is also representative of shipping channel depts. This scenario is especially realistic when combined with rising-type bottom mines.

2. MCM Configurations

a. Legacy

The legacy MCM configuration consists of the MCM 1 *Avenger* class vessels as surface assets paired with the CH-53E Sea Dragon helicopters for airborne MCM. The MCM 1 class vessels utilize sonar to detect and classify mine-like contacts and follow up with a tethered neutralization system to identify and neutralize. The *Avenger* class ships conduct their missions from within the minefield and are designed to mitigate detection by influence mines. This includes wooden hulled construction and engine quieting technologies. These vessels also utilize minesweeping capabilities to cut moored mines from their anchors or detonate influence type mines. A limiting factor of these vessels is their slow transit speed and need for heavy-lift to get them to the theater requiring their capabilities (Frank et al. 2014).

The CH-53E Sea Dragon helicopter is utilized for mine hunting, minesweeping, and mine neutralization missions. This helicopter is deployed from a big-deck ship such as an LHD, but theoretically could operate from shore or other big-deck ship if necessary. The Sea Dragon has less vulnerability to mines as it is an air asset, but it could still be damaged by mines when detonated beneath the helicopter. The CH-53E is limited by its flight time of approximately four hours, and its need to return to base to switch out between hunting systems, sweeping systems, and neutralization systems.

b. Future

The LCS MCM Mission Package consists of the RMS for search and classification, and an SH-60 helicopter for identification and neutralization. The LCS is not intended to operate within the minefield and depends on the RMS to enter and search the minefield. The RMS is launched and recovered from the LCS in order to conduct its

search operations. The SH-60 is also launched and recovered from the LCS (Frank et al. 2014, National Research Council, Committee for Mine Warfare Assessment 2001).

3. MK18 MOD 2

According to the Avenger class platform MCM Embark officer Mark Sergi and MK18 Mod 2 project team member Michael Stuckenschnieder, the MK18 Mod 2 is a surfaced launched search, classification, and identification asset (Mark Sergi, personal comm., Michael Stuckenschnieder, personal comm.). It is operated by explosive ordnance disposal (EOD) teams in the 5th fleet AOR to assist in mine-clearance operations. The MK18 can be launched from small craft utilizing purpose-built carrying cradles. The 11-meter RHIB is one asset utilized for the launch and recovery of the MK18 Mod 2.

4. Overlap

The MCM-1 *Avenger* vessels and the CH-53s are scheduled to be replaced by the LCS MCM mission package by the year 2024 as shown in Figure 14. This figure still presents the intention that the LCS replaces all other MCM platforms in an unknown future end state.

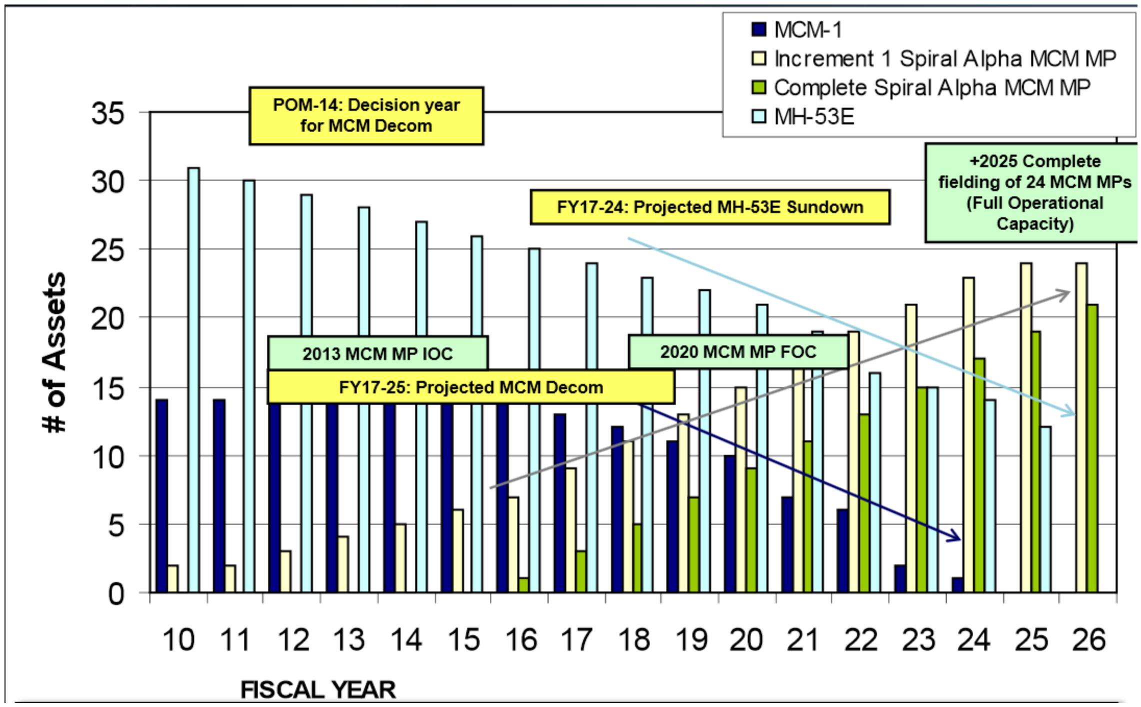

Figure 14. LCS/MCM Overlap (source: Amador 2011)

The MK18 Mod 2 is not part of the intended LCS MCM Mission Package, but the MK18 is a proven asset already operational with EOD units in 5th Fleet. The LCS MCM MP RMS has run into significant problems during its development and testing, and has been recommended for review by the Senate Armed Services Committee in comparison with other MCM search assets (Rear Admiral Rick Williams, USN (Ret), personal comm.). Even before this recommendation, SMEs and fleet representatives were concerned with the RMS performance and had suggested modeling the MK18 Mod 2 in place of the LCS MCM MP RMS.

B. OPERATIONAL CONCEPTS

1. Legacy

The legacy operational concept modeled by the MIW 2014 team involved parallel search and hunt by legacy surface and aviation assets (Frank et al. 2014). As this method of hunt returned the highest ACRS in that study, this is the only legacy configuration that was used for comparison in the MIW 2015 study. This concept relied on a known minefield, split between surface and airborne assets. In this concept, a single MCM-1

Avenger vessel conducts a ladder search in its assigned area, while the CH-53E simultaneously conducts a search of its assigned area. As the MCM-1 vessel detects MILCOs, it conducts immediate identification and neutralization. The CH-53Es require PMA to determine target location and generate a target list. Once a target list is generated, then the CH-53 can be outfitted with a neutralization system in order to prosecute the MILCO.

2. Future

In the "as modeled" LCS MCM Mission Package, the LCS launches the RMS in order to search the minefield. At the completion of each RMS sortie, the data is downloaded and PMA is conducted. Any MILCOs located are added to a target list. Once a target list is available, the MH-60S is launched to identify and neutralize up to four contacts on the target list at a time, dependent on the MH-60's sortie time.

3. MK18 MOD 2

The LCS utilizing the MK18 Mod 2 concept of operations is very similar to the planned LCS MCM MP RMS. However, the MK18 Mod 2 has a significantly slower transit speed and is normally taken to its operating areas by RHIB when used by EOD teams. In the LCS MK18 model, the transit from the LCS to the minefield is conducted by RHIB launched from the LCS. The RHIB transits and then launches the MK18 at the edge of the minefield. The MK18 then executes a search pattern, and based on its battery life will end its search at the same end of the minefield that it was launched on. Then the RHIB picks up the MK18 and transits back to the LCS. Upon recovery aboard the LCS, the data is downloaded and the MK18 is readied for another sortie. PMA generates a target list that is then prosecuted by the MH-60 in the same fashion as for the standard LCS MCM MP. This concept is consistent for multiple MK18s.

C. OPERATIONAL SCENARIO

The operational scenario utilized in this study is the same as utilized by MIW Team 2014. This was done to allow comparisons between that team's findings and data with MIW Team 2015's findings. Their scenario assumed a deep water (>200 ft.) SLOC

scenario in a 10x10 grid (100 NM^2). 100 mines and 400 non-mine contacts were seeded throughout the area. This scenario is representative of many maritime chokepoints such as the Straits of Malacca and Hormuz, shown in Figure 15. The mine density was recommended by experts as a realistic representation of mine and non-mine density. At simulation start, the search assets conduct a ladder search as discussed in their respective concepts. The scenario completes when the complete grid is searched and all targets on the target list have been prosecuted.

Three basic variants MCM variants were compared. Team MIW 2014's legacy configuration 2A was taken for the legacy comparison. This was the legacy configuration tested that had the highest ACRS for that group, and consisted of an MCM 1 *Avenger*-class vessel hunting in parallel with a CH-53E. The LCS variant modeled by Team MIW 2014 utilized the LCS MCM MP Inc 1 configuration as described in Table 4. There is one exception as Team MIW 2014 did not model the shallow water mining capability of the ALMDS as the scenario only utilized deep water mines.

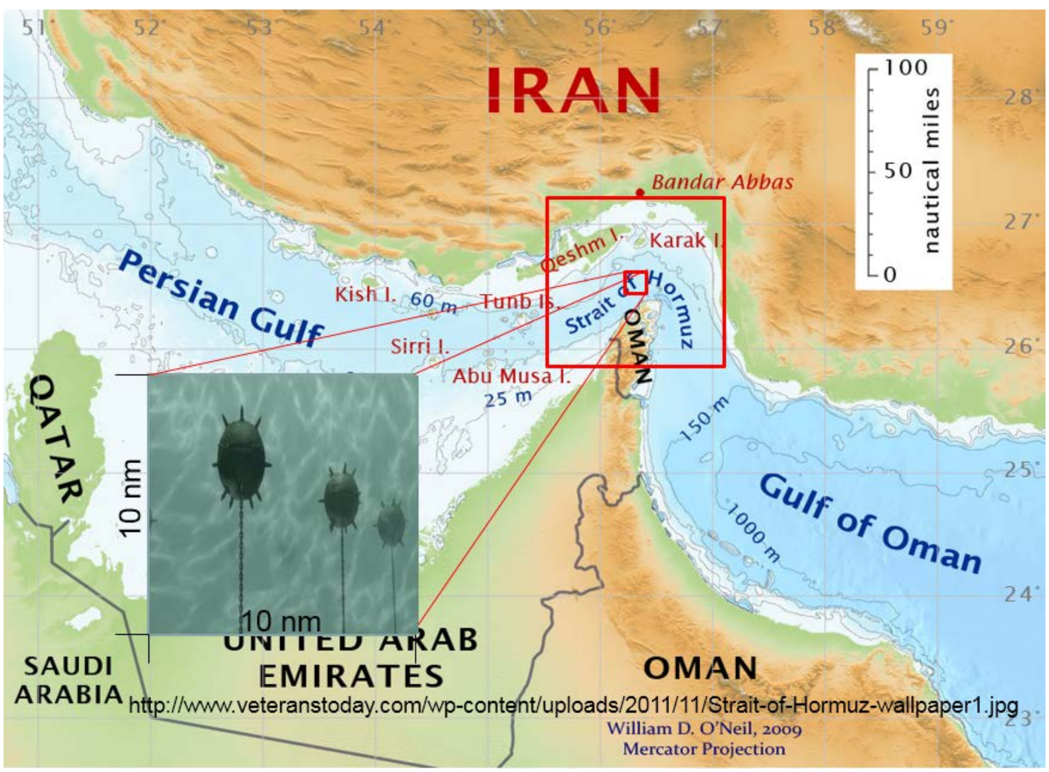

Figure 15. Operational Scenario MIW 2014 and 2015

Table 4. MCM Mission Package Increments (adapted from Frank et al. 2014)

MCM Mission Package	INC 1	INC 2	INC 3	INC 4	Capability
Airborne Laser Mine Detection System – SH-60S surface mine detection system	X				Detect, classify, and localize near surface mines
Airborne Mine Neutralization System – SH-60S carried mine neutralization system	X		X*		Identify and neutralize bottom and moored mines in shallow water. *add near surface mines
AN/AQS-20A – RMS carried mine detection sonar	X				Detect, localize, classify of bottom mines in deep water
Remote Mine hunting System – Large Multi-Mission UUV transported and launched from the LCS	X				Remote vehicle that tows AN/AQS-20A
Coastal Battlefield Reconnaissance and Analysis System – UAV for beachhead minefield detection		X			Provide intelligence preparation for the minefield
Unmanned Influence Sweep System – Unmanned surface vessel towing influence sweeping systems			X		Unmanned surface vehicle that tows an influence sweep

Finally, 11 separate MK18 Mod 2 configurations were modeled, corresponding to different numbers of MK18s utilized to perform the search function. Table 5 graphically depicts the different configurations utilized in this study. The modeled performance data for configurations 2A and 3 were taken directly from Team MIW 2014's report for comparison to Team MIW 2015's modeled MK18 data. The only difference between the various modeled MK18 configurations was the number of MK18s.

Table 5. MCM Configurations

Configuration	Platform	Helicopter	Subsystems
2A	Legacy MCM 1	MH-53-E	MCM 1: AN/SQQ-32, SLQ-48 MH-53E: AN/AQS-24 Hunt Method: Serial
3	LCS	MH-60s	LCS: RMS with AN/AQS-20, MH-60s: Archerfish Hunt Method: Serial
1M	MK18	MH-60s	LCS: MK18 Mod 2, MH-60s: Archerfish Hunt Method: Serial
2M	MK18	MH-60s	LCS: MK18 Mod 2, MH-60s: Archerfish Hunt Method: Serial
3M	MK18	MH-60s	LCS: MK18 Mod 2, MH-60s: Archerfish Hunt Method: Serial
4M	MK18	MH-60s	LCS: MK18 Mod 2, MH-60s: Archerfish Hunt Method: Serial
5M	MK18	MH-60s	LCS: MK18 Mod 2, MH-60s: Archerfish Hunt Method: Serial
6M	MK18	MH-60s	LCS: MK18 Mod 2, MH-60s: Archerfish Hunt Method: Serial
7M	MK18	MH-60s	LCS: MK18 Mod 2, MH-60s: Archerfish Hunt Method: Serial
8M	MK18	MH-60s	LCS: MK18 Mod 2, MH-60s: Archerfish Hunt Method: Serial
9M	MK18	MH-60s	LCS: MK18 Mod 2, MH-60s: Archerfish Hunt Method: Serial
10M	MK18	MH-60s	LCS: MK18 Mod 2, MH-60s: Archerfish Hunt Method: Serial
12M	MK18	MH-60s	LCS: MK18 Mod 2, MH-60s: Archerfish Hunt Method: Serial

D. OPERATIONAL CONCEPT AND SCENARIO SUMMARY

The legacy, LCS and MK18 Mod 2 concepts of operations were discussed and described as modeled for this project. The relationship of the Team MIW 2014 capstone project with this project was discussed, as was the decision to keep the data from both studies comparable by utilizing the same operational scenario. Finally, all configurations utilized were defined for easy reference.

V. SYSTEMS ARCHITECTURE

MCM system architectures based on the legacy Avenger class MCM 1, the current LCS MCM Inc 1, and the alternative MK18 Mod 2 system are detailed in this chapter. This chapter also contains the functional and physical hierarchies for the MCM system. For this capstone project, physical developments of a new system were not analyzed. Modeling and simulation utilizing ExtendSim was conducted to represent the actual systems for the analysis. Understanding the system architecture was required for traceability of the component functional and physical architectures to their specific system functions as described in the systems engineering process chapter. The main goal was to gain an understanding of the MIW systems from a SE perspective rather than developing a new MIW proof of concept model that would be used for MCM analysis.

A. FUNCTIONAL HIERARCHY

According to Blanchard and Fabrycky (2011), "functional analysis is an iterative process of translating system requirements into detailed design criteria. The purpose is to develop the top level system architecture and present an overall integrated description of the systems functional architecture" (86). The functions that are performed in MCM operations aid in the definition of the architecture. Decomposing these functions resulted in the functional architecture for the MIW project. The functional architecture is described in this chapter.

1. Top Level Functional Hierarchy

This study will focus on the mine hunting operations in deep water (water depths greater than 200 feet). The top level functional hierarchy for MIW is illustrated in Figure 16. The primary functions associated with mine hunting are highlighted in green and the functions highlighted in grey are functions that are not part of this study. The functions highlighted in orange and blue are necessary in order to capture and analyze the ACRS for the operation. They include the control equipment functions and the analyze function data respectively. Finally, the maintain equipment function contains the ACRS and the conduct of the mission affected by operational availability (Ao).

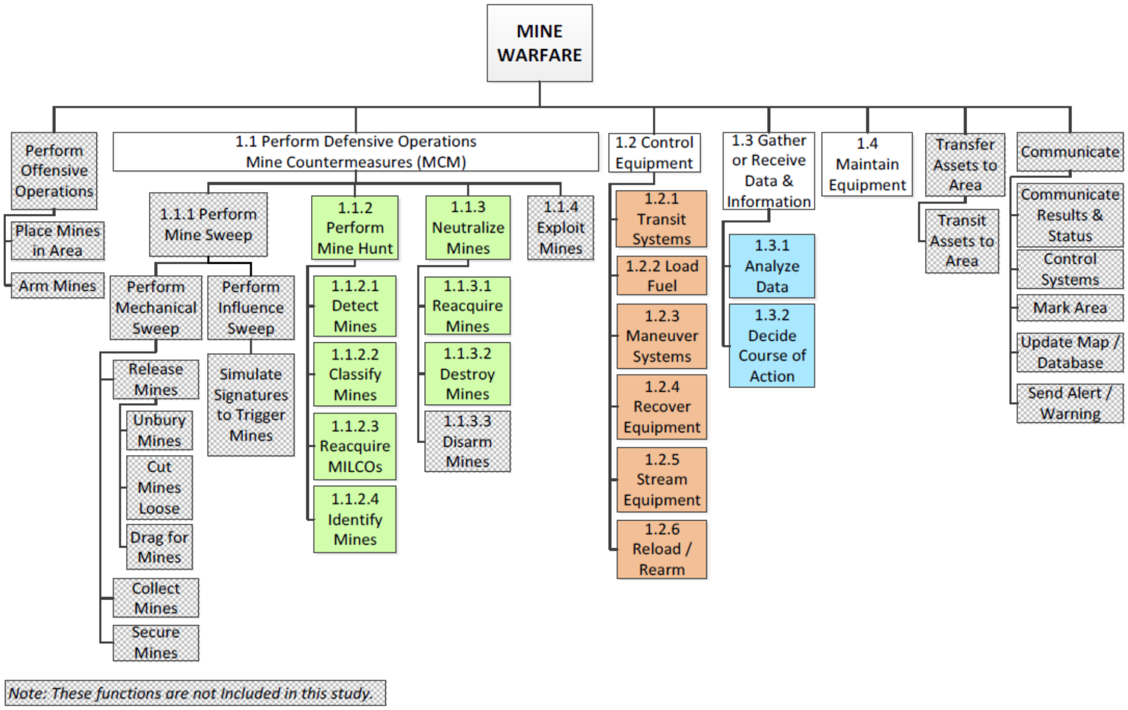

Figure 16. MIW Function Hierarchy (source: PEO LMW 2009)

2. Mine Hunting Functional Hierarchy

Figure 17 depicts the functional hierarchy view of the MCM model. For this study, perform minesweeping, disarm mine, and analyze mine are not included. The remaining functions are described and each one is explained within this chapter.

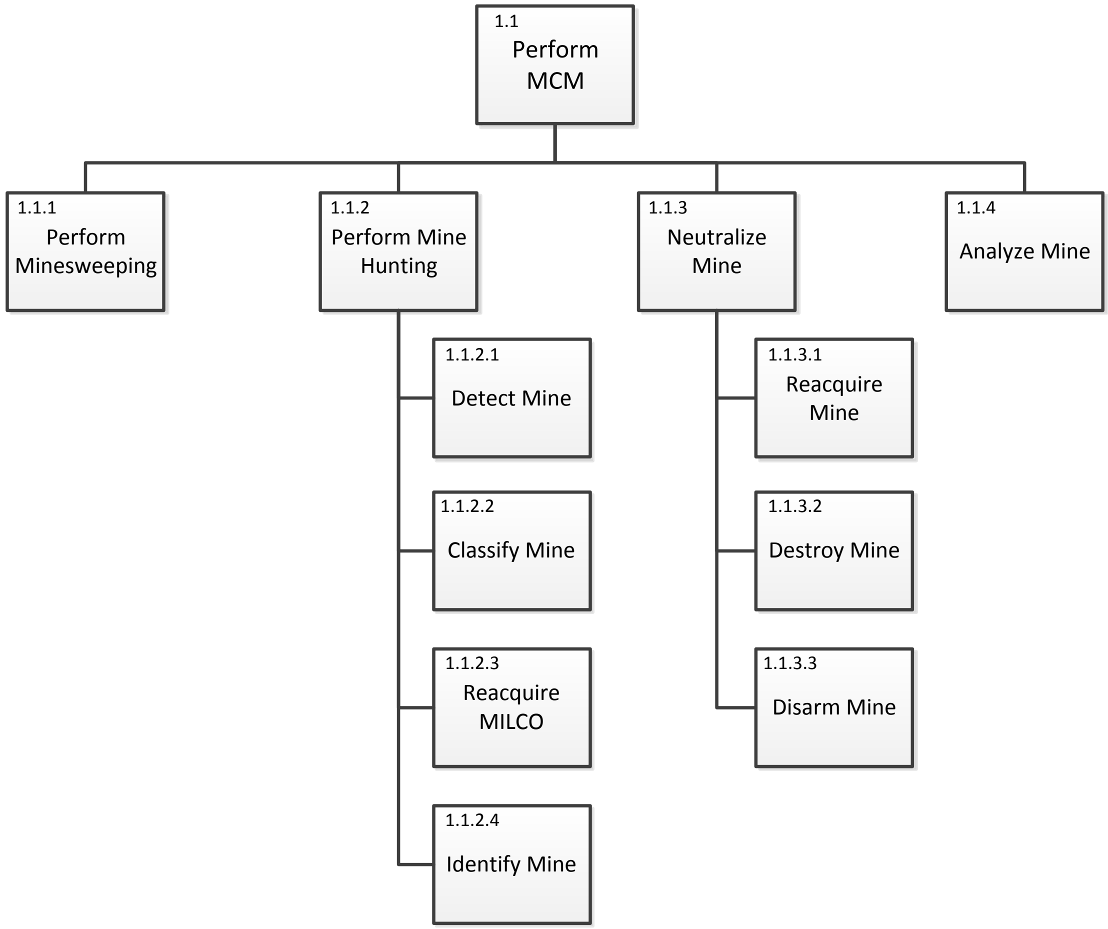

Figure 17. Mine Hunting Functional Hierarchy (adapted from Frank et al. 2014)

a. Detect Mine

The first phase in performing mine hunting is to detect and look for what are perceived as mines by sending out pings. This is typically performed by sensing. Using sensors, the systems detect these pings from mines, the seafloor, and other objects floating in the waters. At the completion of the detection, the system reports if there are mines and/or possible mines within the vicinity that was scanned. If no possible mines are detected, the system continues onto the next scan area and the results are communicated to the personnel and other ships in the area. Objects that are detected as a mine-like echo (MILEC) proceed to the next sequence for classification.

b. *Classify Mine*

After an object is distinguished as a MILEC, they must be classified as either a MILCO or a non-MILCO. This function is executed to distinguish which MILECs have a high probability of being an actual mine. This information is used to further investigate those objects and determine which are mines and which are not mines.

c. *Reacquire MILCO*

This function is performed when a different system is used in the identification phase. Reacquiring MILCO involves the tasks to search for and find the signal sources so they can be investigated and identified as mines or non-mines.

d. *Identify Mine*

The identification phase analyzes the MILCO objects and determines if they are mines or non-mines. The type and location of the mines are then communicated to the appropriate personnel, supporting platform, and the other ships in the area. The results are then fed into the neutralization phase which marks the area as a minefield to warn unsuspecting vessels.

e. *Neutralize Mine*

The neutralize mine function eliminates the function of mine so they cannot explode and cause unwanted damage. This is done by either detonating the mines or by disarming them. For this study, the focus is on destroying the mines.

f. *Reacquire Mine*

Similar to the Reacquire MILCO function, this reacquisition function is performed when a different system is used for neutralization. Again, this function involves the tasks to search for and find the mine signal sources so that they can be neutralized.

g. *Destroy Mine*

The mine destruction function involves finding the mine-like objects and destroying the ones that are perceived as mines so that, when detonated, explosions do not cause damage or harm. For this study, an airborne asset was used to destroy the mines.

3. MIW Operational Flow Diagram

Figure 18 depicts the top level functional flow block diagram of the MK18 Mod 2 model. Within this chapter are decompositions or sub-functions of the main system.

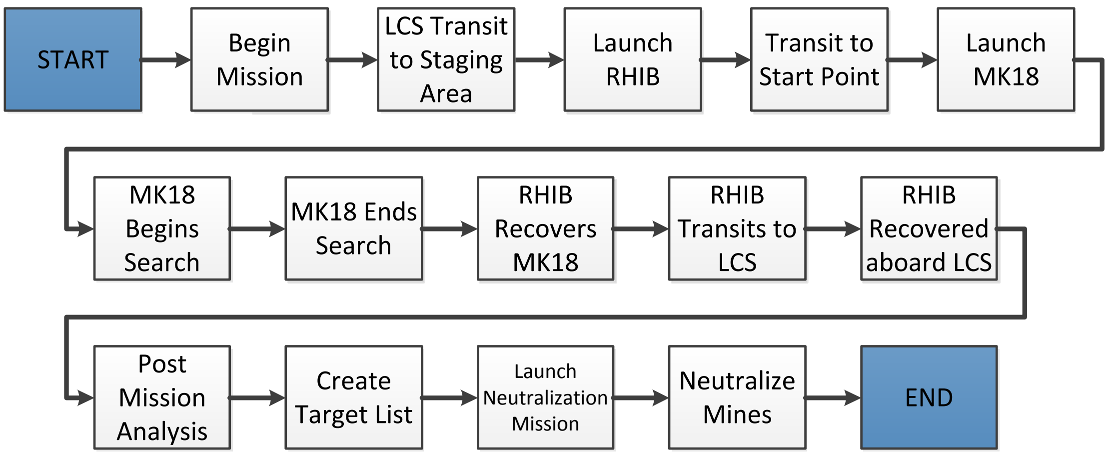

Figure 18. MK18 Mod 2 Operational Flow Diagram

a. *Begin Mission*

This is the first stage in a mine hunting mission. Orders are received to begin a new mission utilizing the MK18 Mod 2 UUV.

b. *LCS Transit to Staging Area*

At this state, the LCS equipped with a RHIB and MK18 Mod 2 transits to the safe zone mine hunting staging area.

c. *Launch RHIB*

A RHIB hosts one or more MK18 Mod 2's and is located on an LCS platform. This function is the launching of the RHIB into the water.

d. Transit to Start Point

The RHIB that was just launched transits to the starting point where the MK18 Mod 2 is set for release. This is a predetermined spot at the location of the targeted search area.

e. Launch MK18

The MK18 Mod 2 is released from the RHIB into the water at the predetermined spot of the minefield search area. From here, the MK18 Mod 2 is ready to start its mine hunting mission.

f. MK18 Begins Search

The MK18 Mod 2 begins to scan and sense the uncharted minefield area for mine-like objects. Any findings are recorded to the onboard memory.

g. MK18 Ends Search

At the completion of the scan area, the MK18 Mod 2 finishes all of its passes along a dedicated path and is awaiting recovery from a RHIB. The MK18 Mod 2 plans its search to end on the same side it was released regardless of finishing its search before all of its energy is utilized. All data collected is stored in local memory ready to be analyzed.

h. RHIB Recovers MK18

This function describes the RHIB as it retrieves the MK18 Mod 2 from the open water. It is loaded onto the RHIB awaiting transport to the LCS platform.

i. RHIB Transits to LCS

As the RHIB equipped with the MK18 Mod 2 transits away from the search area, it makes its way to the LCS where it will be stowed.

j. RHIB Recovered aboard LCS

This function describes the recovery of the RHIB as it makes its way to the LCS for stowage and extraction of MK18 Mod 2 data collection.

k. Post Mission Analysis

This is where the data captured from the search area via the MK18 Mod 2 is extracted and analyzed for mine and non-mine objects. This is where threat and/or non-threat classifications are made.

l. Create Target List

Upon completion of the PMA, a list of generated mine threats are compiled. From here, the listing is disseminated to the personnel and platforms that will be engaging in or near the conducted search area.

m. Launch Neutralization Mission

After receiving the mine target list, a MH-60S is tasked to neutralize the mines.

n. Neutralize Mines

At this state, the MH-60S that was deployed searches for and neutralizes the objects that were classified as mines during the initial hunt by the MK18 Mod 2.

B. PHYSICAL HIERARCHY

This report focuses on the comparison of the legacy MCM MP – MCM 1 the current LCS MCM Inc 1, and the future MCM MP – MK18 Mod 2. The MCM functions described above are performed by several systems. Figure 19 shows the first three levels of MCM Systems with the legacy MCM 1, the LCS MCM Inc 1 that relies on the LCS remote multi-mission vehicle (RMMV) configured as the RMS to perform mine hunting, and the MK18 Mod 2 which is being evaluated in place of the current RMS.

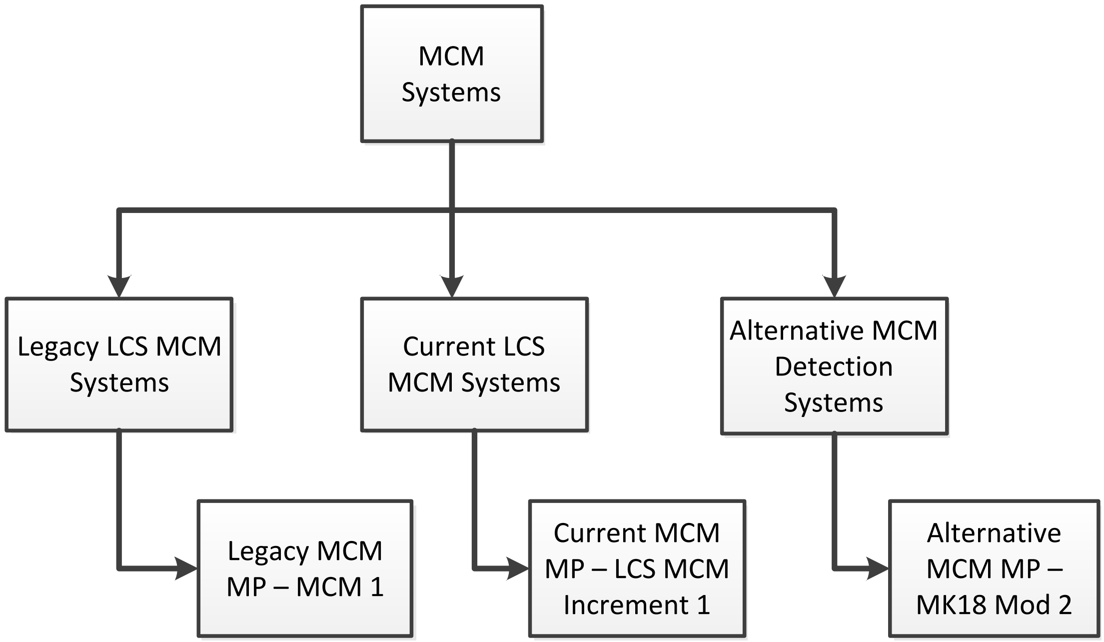

Figure 19. MCM System Physical Hierarchy

1. MCM 1

"The Avenger class MCM 1 ships were designed as mine hunter-killers capable of finding, classifying and destroying moored and bottom mines" (Global Security 2011, 1). Their main goal was to detect, classify, and neutralize all objects classified as mines and mine-like objects with the primary mission objectives of mine hunting, mine neutralization, and mine sweeping. "The MCM 1 navigates and clears minefields by first sweeping the search areas and also conducts coordinated operations with airborne and other mine countermeasure forces" (Global Security 2011, 1).

2. LCS MCM Inc 1

LCS is "intended to accommodate a variety of individual warfare systems assembled and integrated into four interchangeable mission packages" (Spilman 2013, 1). For this study, the LCS MCM Inc 1 was analyzed.

The Inc 1 mission package includes "the RMS which consists of the RMMV and the AN/AQS-20A sonar system" (Global Security 2014, 235). It also incorporates "the MH-60S Block 2A/B Airborne Mine Countermeasures (AMCM) System which consists

of an AMCM system operator workstation, a tether system, and the two MCM systems currently under development – ALMDS for detection and classification of near surface mines, and the AMNS for identification and neutralization of bottom mines" (Global Security 2014, 239).

3. MK18 Mod 2

The MK18 Mod 2 is an autonomous UUV that is in operation and "used by the U.S. Navy for mine detection missions with an improved endurance and area coverage rate that replaces the in-theater Swordfish system" (Naval Surface Warfare Center Panama City Division Public Affairs 2013, 1). The MK18 Mod 2 is normally taken to its operating areas by RHIB when used by EOD teams. The RHIB transits and then launches the MK18 Mod 2 at the edge of the minefield. "The UUV is pre-programmed and designed to scan waters for targets or threats" (Naval Surface Warfare Center Panama City Division Public Affairs 2013, 1). The UUV then executes a search pattern, and based on its battery life will end its search at the same end of the minefield that it was launched on. Afterwards, the RHIB picks up the MK18 Mod 2 and transits back to the LCS. Upon recovery aboard the LCS, the data is downloaded and the MK18 Mod 2 is readied for another sortie. Finally, PMA generates a target list that is then prosecuted by the MH-60.

C. SYSTEMS ARCHITECTURE SUMMARY

This chapter focused on the functional and physical hierarchies of MIW. Diagrams were developed to represent the functions of interest for mine warfare operations within the predefined 10x10 grid (100 NM^2) scenario. The functional hierarchy was further decomposed to an overall MIW diagram, the mine hunting functional hierarchy, and the operational flow of the MK18 Mod 2. The decomposed diagrams aided in the development of the simulation model and were modified accordingly in order to satisfy stakeholder requirements.

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VI. MODELING AND SIMULATION DEVELOPMENT

This chapter discusses the modeling and simulation (M&S) approach applied as a result from following the tailored SE process described earlier to select the method to generate the necessary data for analysis. The chapter details the processes implemented during the initial evaluation of the provided model, subsequent analysis of alternatives and eventual down select to a modeling approach. Modeling and simulation with known data points was performed to ensure that a successfully modified model, codenamed ARMS, existed and functioned to provide valuable information to the stakeholder community.

A. MODEL EVALUATION AND ANALYSIS

Using a tailored SE process, the team focused the study on the evaluation of legacy, current and the potential alternative of inclusion of the MK18 Mod 2 within a standardized MIW reference mission. Through modeling and simulation the MOE and MOP, as determined through stakeholder analysis, were measured to derive the overall effectiveness within the reference mission providing decision makers insight for further research or planning. As this capstone project was performing follow-on work to the 2014 MIW effort, the prior team's ExtendSim models were provided by the NPS staff for baseline use and extension in this study. The ExtendSim modeling and simulation tool implements a graphical programming environment, supplemented by additional user developed code, in which the model developer can implement configurable items in structured connections to replicate the desired activity under study. The models provided were constructed in a modular fashion, separating the mission into high level functional blocks of search, PMA and neutralization. With each high level block decomposing into lower level functions required to replicate the mission scenarios accurately. While the two provided models were similar in replicating the mission plan, they differed slightly in their makeup as the legacy includes the capability of the seaborne assets to perform both the hunt and neutralization aspects of the mission. The model was kept intact as part of this study to provide comparative baseline information.

B. FEASIBILITY

To begin the analysis of modeling capabilities, the MCM MP Inc 1 model was examined to determine break points and modules for code reuse or adaption. Further reverse engineering was performed, in which differing modification strategies were applied for consideration with intermediate results analyzed during regular meetings among the MIW 2015 team. The primary portions of the existing 2014 model requiring modification for extended study were the search and PMA portions of the modeled mission. One method considered involved duplicating the search function of the single asset, modified with additional transit time for a single RHIB to place MK18 Mod 2 at the appropriate starting locations within the search grid.

C. IMPLEMENTATION

To satisfy the stated desires of the stakeholder community, simulations to determine the approximate number of MK18 Mod 2 devices that would equate to the search effectiveness of the legacy and LCS MP1 were created from the ExtendSim LCS MP1 model. A separate cost analysis was performed using the significant variables to arrive at the appropriate cost estimation figures of all multiples of MK18 Mod 2 employed. The methodology, results and conclusions are included in Chapter IX. To achieve the goal, a strategy to modify the single hunt search area to extrapolate the use of multiple MK18 Mod 2s performing the search functions was presented to the advisors after receiving concurrence on the approach during the 3 August 2015 meeting with NMAWC MIW requirements N8 Richard Kimmel. In this approach, the number of search targets, both mines and non-mines, were kept constant and the search grid width modified as required for the number of MK18 Mod 2 for data gathering and analysis. Using the performance parameter variations obtained during stakeholder analysis and feedback from the SME, model runs were performed in accordance with the requirements of the nearly orthogonal Latin hypercube (NOLH) stated in Chapter VII.

D. MODEL VERIFICATION AND VALIDATION

After determining the model and strategy to be implemented, the various configurations were subjected to verification and validation processes to ensure the data

produced during the "run for record" would produce valid information. Following the intent of Department of Defense (DOD) Instruction (DODI) 5000.61, "DOD Modeling and Simulation (M&S) Verification, Validation, and Accreditation (VV&A)" (Under Secretary of Defense for Acquisition, Technology, and Logistics (AT&L) 2009) the verification of the model ensured produced data "accurately represent the developer's conceptual description and specification" (DODI 5000.61, 2009). In similar fashion validation of the model was performed and the resultant data to ensure that both were "an accurate representation of the real world from the perspective of the intended uses of the model" (DODI 5000.61, 2009).

1. Verification

During the verification process of a project the determination of whether the requirements were met is performed. The verification of requirements can be adjudicated through various methods; analysis, testing, inspection or demonstration via either a physical or simulated event. As the majority of the requirements for this project were of allowable ranges of performance, the numerical outputs produced by the corresponding input values was verified as accurate through the inspection of the code.

2. Validation

The validation process of a system measures how well it matches to the stakeholder's expressed need. In this project, since the input parameters were all of sanitized unclassified data, the ranges provided were representative producing only generalized results. Since the stakeholder's stated need was for a tool to perform a comparison between multiple alternatives, each using similar sanitized parameters, there was not a need for results that would be similar to actual system performance because that would potentially produce classified results. Within the model, the MOE determined to be most significant to the operational mission were that of ACRS and percent clearance. Results of model runs were provided to SMEs for feedback on the reasonableness of the results. As such the model produced representative data that satisfied the stakeholder's expectations, and was considered as being sufficiently valid.

E. MODELING AND SIMULATION CONCLUSION

Development, testing and implementation of a modeling and simulation approach were achieved through multiple iterations leveraging a DOE approach. Although the DOE portion of this project is detail expressly in Chapter VII, it was used extensively in the analyses of all model iterations to ensure that proper data could be produced and replicated prior to commitment to the selected approach. While there remain questions to explore regarding the implementation of multiple neutralization assets, the model and strategy implemented does provide the requisite data points to produce a comparison between legacy, current, and future alternative MIW assets.

VII. DESIGN OF EXPERIMENTS

A design of experiments was conducted prior to entering the modeling and simulation phase of the project. This was accomplished to ensure that a sufficient number of model runs were conducted to minimize potential undesired correlation between input variables and to maintain statistical significance. The resulting data could then be used to determine which variable input factors were of most influence to ACRS and percent clearance.

A. VARIABLES OF INTEREST

A subset of existing model variable input factors were looked at both from a perspective of factors that were previously investigated as well as those that applied to configurations relevant to utilizing the MK18 Mod 2 as the hunt/classification asset. Table 6 shows the variable input factors that were investigated. A total of 38 surface hunt and air parameters were considered in the model, but only 20 of those were variable factors. Each factor listed below is shown with its corresponding input value range (min and max). The air asset factors were kept the same as those values used in the previous project since it was not the purpose of this project to investigate air asset factors. Varying these factors may also have had a negative impact to those surface factors that were the subject of interest.

Table 6. Variable Input Factor Description and Ranges

Input Factor	Factor Description	LCS config 3		LCS with MK18	
		Min	Max	Min	Max
S_SearchSpeed_kt	Surface search speed	5	10	3	5
S_TurnTime_s	Surface turn time at end of track	300	600	160	200
S_TransitSpd_kt	Surface transit speed from staging area to minefield	20	50	20	40
S_NumHntTrk_pNM	Surface hunt tracks per nautical mile	20	20	26	34
S_SStreamT_hr	Surface time to stream search equipment	0.25	2	0.508	1.5

(continued on next page)

Table 6 (continued from previous page)

Input Factor	Factor Description	LCS config 3		LCS with MK18	
		Min	Max	Min	Max
S_SRecoverT_hr	Surface time to recover search equipment	0.25	2	0.003	0.34
S_Replenish_hr	Surface replenish time	2	4	1.5	15
S_SortieTime_hr	Surface max sortie time	10	20	15	20
S_Pd	Surface probability of detecting a MILEC	0.70	0.90	0.60	0.85
S_Pcmm	Surface probability of classifying a MILEC as a MILCO	0.7	0.9	0.5	0.9
S_Pcnn	Surface probability of classifying a non-MILEC as a MILCO	0.7	0.9	0.5	0.9
A_TransitSpd_kt	Airborne transit speed from staging area to minefield	80	150	80	150
A_ReplenishT_hr	Airborne time to replenish neutralizers	1	2	1	2
A_Prmm	Airborne probability of reacquiring a MILCO as a MILCO	0.70	0.80	0.70	0.80
A_Prnn	Airborne probability of reacquiring a MILCO as a non-MILCO	0.20	0.30	0.20	0.30
A_Pimm	Airborne probability of identifying a MILCO as a mine	0.70	1.00	0.70	1.00
A_Pn	Airborne probability of neutralizing a mine	0.70	0.90	0.70	0.90
A_RDeployT_hr	Airborne time to deploy reacquisition and identification equipment	0.25	0.50	0.25	0.50
A_RRecoverT_hr	Airborne time to recover reacquisition and identification equipment	0.25	0.50	0.25	0.50
A_NeutSpeed_kt	Airborne neutralizer speed	2.50	5.00	2.50	5.00

Some key differences between surface model input factors were the result of the different hunt asset used (MK18 vs. RMS). Most notably the surface search speed for the MK18 Mod 2 is much slower than that of the RMS despite having a faster turn time. Another significant element accounting for the varying ranges in surface hunt factors can be attributed to the requirement to keep all data used throughout the investigation unclassified. This required the need for data ranges that both included and masked the true values. In addition, the probability of detection (S_Pd), the surface probability of classifying a MILEC as a MILCO (S_Pcmm), and the surface probability of classifying a non-MILEC as a MILCO (S_Pcnn) ranges used were greater than that used by the previous project team. These changes were directly involved in differences seen in mine detection. The remaining 18 factors used within the simulation were held at constant values, either zero or some other constant value.

B. DESIGN OF EXPERIMENTS

Once the factors of interest were identified the necessary model input data required proper formatting to run model simulations. NOLH design spreadsheets (Sanchez 2011) were used to generate the required data. The NOLH spreadsheets take variable ranges as input by the user and generates data for simulations, dependent on the number of factors. For the 20 factors of interest it was determined, as a result of using the NOLH spreadsheet, that 129 runs would be required to minimize potential unwanted correlations between input variables. "It takes extensive time to generate these designs using our algorithm; therefore, a catalogue of ready-to-use, nearly orthogonal and good space-filling designs for up to 22 factors in as few as 129 runs has been given by Cioppa (2002) and available for download at http://harvest.nps.edu (Cioppa and Lucas 2007, 45). Because the t-distribution begins to approach the normal distribution at around 30 degrees of freedom, it was determined that 3,870 runs (129 runs x 30 replications) would be required for each configuration under investigation. While preventing unwanted correlation between input factors, the NOLH spreadsheet also ensured that the variation between variable input factors was evenly distributed. JMP™ statistical software was used to perform data analysis of the resulting 46,440 total model runs performed across

all MK18 configurations under investigation. Table 7 displays results from this analysis to include the mean ACRS and percent clearance for each configuration as well as the lower and upper 95% confidence interval.

Table 7. Mean and 95% Confidence Interval for ACRS and % Clearance

	ACRS			Percent Clearance		
	Mean	95% Confidence Interval		Mean	95% Confidence Interval	
Configuration		Lower	Upper		Lower	Upper
2A	5.35	5.25	5.45	0.33	0.32	0.34
3	4.80	4.71	4.89	0.33	0.32	0.34
1M	1.80	1.79	1.81	0.26	0.26	0.26
2M	3.51	3.48	3.54	0.26	0.26	0.26
3M	5.00	4.96	5.03	0.26	0.26	0.26
4M	6.05	6.01	6.09	0.26	0.26	0.26
5M	6.72	6.67	6.76	0.26	0.26	0.26
6M	7.18	7.13	7.23	0.26	0.26	0.26
7M	7.40	7.35	7.46	0.26	0.26	0.26
8M	7.59	7.53	7.65	0.26	0.26	0.26
9M	7.71	7.64	7.77	0.26	0.25	0.26
10M	7.80	7.73	7.86	0.26	0.26	0.26
12M	7.95	8.01	8.01	0.26	0.26	0.26

ACRS is calculated by

$$ACRS = \frac{Area}{T_{\text{Total}}}$$

Area = Total area covered by hunt asset

T_{Total} = Total mission time divided by 24 hours

While percent clearance is calculated by

$$\%\,Clearance = \frac{Mines\ successfully\ neutrilized}{Total\ number\ of\ mines}$$

The data resulting from the multiple model runs was analyzed using JMP™ statistical software. The mean of both ACRS and percent clearance is presented in Figure 20 and Figure 21. These figures plot the ACRS and percent clearance for each MCM configuration. The MK18 Mod 2 configurations simply vary the number of MK18s

simulated, and these are listed as 1M-10M, 12M. Configuration 2a and 3 are carried over from team MIW 2014 and are representative of the legacy MCM 1 Avenger and CH-53E hunting in parallel, and the LCS MCM MP increment 1, respectively.

Legacy configuration 2a was seen to have an ACRS of 5.34 with a percent clearance of 32%. LCS configuration 3 had an ACRS of 4.8 with a percent clearance of 33%. From the ACRS plot in Figure 20, it can be seen that an LCS configuration 4M using 4 MK18s exceeds the ACRS performance of both the legacy 2a and LCS configuration 3 by 0.70 and 1.25 respectively.

Percent clearance was seen to drop below that of legacy configuration 2a and LCS configuration 3 values by approximately 6.5%. This can be attributed to the lower ranges in classification and the difference in ranges used for surface probability of detection for the previous project (0.70 to 0.90) and those used for this project and the MK18 (0.60 to 0.85), as well as the lower probability of classifying a mine as a mine given for the MK18 (0.50 to 0.90 as compared to 0.70 to 0.90 for the RMS). With a lower range, it was expected and verified by simulation results that a lower percent clearance would be seen.

When surface probability of detection increases, more mines are detected resulting in a reduction in ACRS. Configurations of 1 through 10 MK18s were the primary focus areas of this study but after plotting the results in the initial plots of Figure 20 for up to 10 MK18s, it was noted that as additional MK18s were added to the simulation the plot began to asymptotically approach an ACRS of somewhere around 8. The 12 MK18 run was an excursion to see what was occurring past 10 MK18s and if the plot still asymptotically approached a value close to 8 as expected. As seen in Figure 20, the 12 MK18 Mod 2 configurations seem to go against the theory that additional MK18s beyond 10 will asymptotically approach an ACRS of around 8. The graph appears to be approaching another ACRS value, but the increase is still not as dramatic as lower MK18 configurations. Further investigation would be required to see what is occurring beyond 12 MK18s.

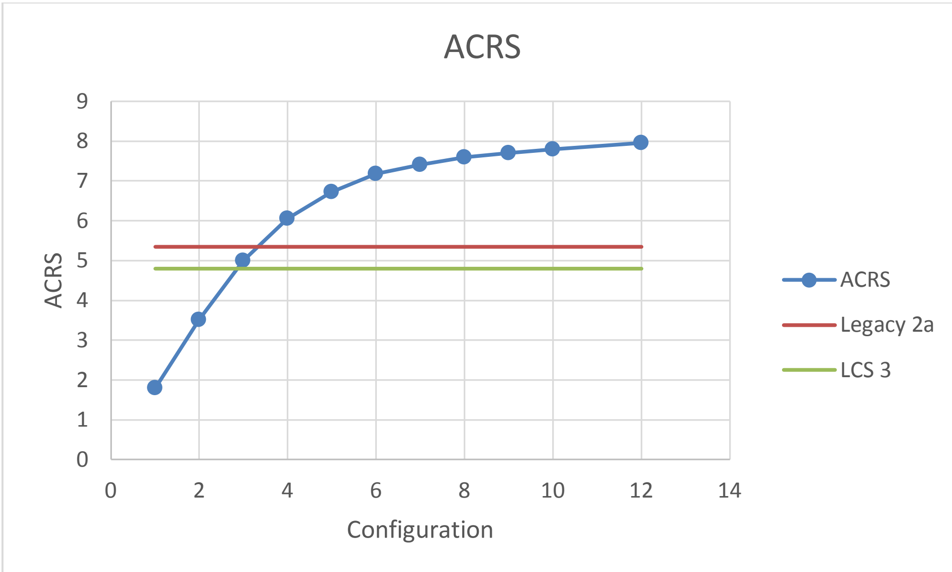

Figure 20. Mean of ACRS vs. Configuration

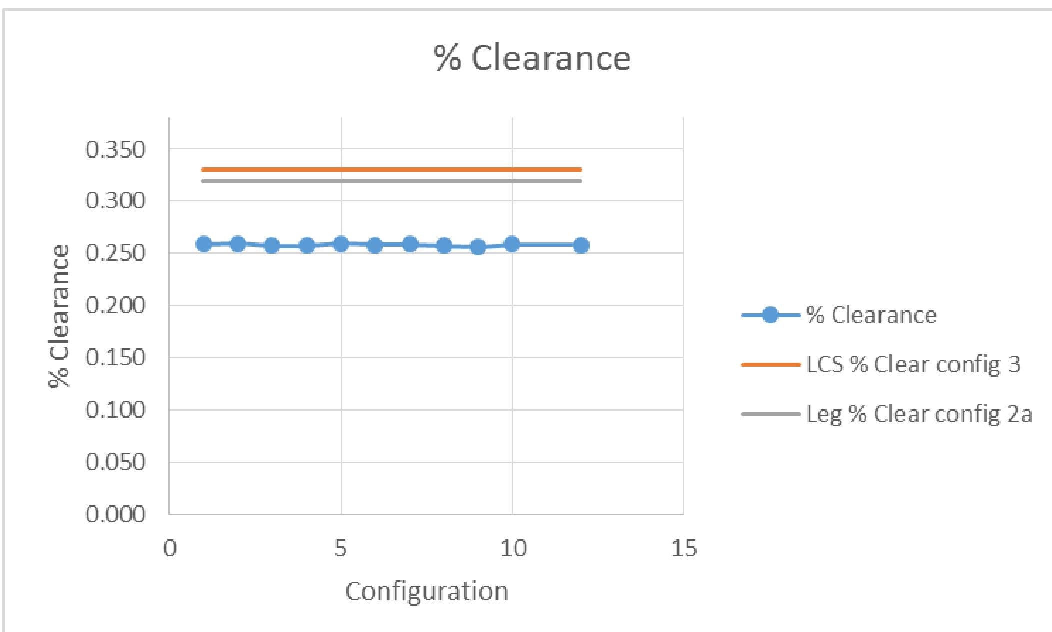

Figure 21. Mean of Percent Clearance vs. Configuration

The top three significant factors for each MK18 configuration are shown in Table 8. They consisted of surface replenish time (S_Replenish_hr), surface search speed (S_SearchSpeed_kt), number of search hunt tracks per nautical mile (S_NumHntTrk_pNM), probability of classifying a non-mine as a non-MILCO (S_Pcnn), and surface probability of detecting a MILEC (S_Pd). Airborne time to recover reacquisition and identification equipment (A_RRecoverT_hr) was omitted from the variables of interest primarily because air factors were not the focus of this study. It also never ranked higher than third as a predictor. This analysis was accomplished by running a fit model in JMP™ with all 38 factors as model effects with ACRS and percent clearance. A stepwise regression allowed for a subset of effects to be chosen for the regression model. This also improved the model's prediction capabilities by reducing variance caused by estimating unnecessary terms. Table 9 shows the absolute value of the t-ratio for each factor of interest. The t-ratio tests if the true value of the parameter in question is zero. The t-ratio itself is the standard error. This study's primary focus was to compare the hunt effectiveness of various configurations consisting of anywhere from 1 to 10 MK18s to that of the RMS' hunt effectiveness.

Table 8. ACRS Top Three Significant Factors

Configuration	1	2	3
1M	S_Replenish_hr	S_SearchSpeed_kt	S_NumHntTrk_pNM
2M	S_Replenish_hr	S_SearchSpeed_kt	S_NumHntTrk_pNM
3M	S_Replenish_hr	S_SearchSpeed_kt	S_NumHntTrk_pNM
4M	S_Replenish_hr	S_Pcnn	S_SearchSpeed_kt
5M	S_Pcnn	S_Replenish_hr	S_SearchSpeed_kt
6M	S_Pcnn	S_Pd	S_Replenish_hr
7M	S_Pcnn	S_Pd	A_RRecoverT_hr
8M	S_Pcnn	S_Pd	A_RRecoverT_hr
9M	S_Pcnn	S_Pd	A_RRecoverT_hr
10M	S_Pcnn	S_Pd	A_RRecoverT_hr
12M	S_Pcnn	S_Pd	A_RDeploy_hr

Table 9. ACRS Absolute Value of t ratio for Significant Factors

Configuration (# MK18)	ACRS Mean	S_Replenish_hr	S_SearchSpeed_kt	S_Pcnn	S_Pd
		|t ratio|			
1	1.800	185.40	160.90		
2	3.510	169.40	152.35		
3	5.000	100.40	91.42		
4	6.050	66.65	56.65	57.08	
5	6.720	47.92	32.44	82.78	
6	7.180	33.27		102.16	39.37
7	7.400			116.14	44.92
8	7.590			116.26	46.39
9	7.710			111.57	43.14
10	7.800			104.49	42.25
12	7.950			96.87	37.44

The top three significant factors for percent clearance are presented in Table 10. Surface probability of classifying a MILEC as a MILCO (S_Pcmm) dominates the top position with airborne probability of identifying a MILCO as a mine (A_Pimm) and Surface Probability of detecting a MILEC (S_Pd). Again, since the air asset was not the primary focus of this project S_Pd was chosen as a factor of interest over A_Pimm although both factors had t ratios that were very close together.

Table 10. Percent Clearance Top Three Significant Factors

Configuration	1	2	3
1M	S_Pcmm	A_Pimm	S_Pd
2M	S_Pcmm	A_Pimm	S_Pd
3M	S_Pcmm	S_Pd	A_Pimm
4M	S_Pcmm	A_Pimm	S_Pd
5M	S_Pcmm	A_Pimm	S_Pd
6M	S_Pcmm	A_Pimm	S_Pd
7M	S_Pcmm	A_Pimm	S_Pd
8M	S_Pcmm	A_Pimm	S_Pd
9M	S_Pcmm	A_Pimm	S_Pd
10M	S_Pcmm	A_Pimm	S_Pd
12M	S_Pcmm	A_Pimm	S_Pd

Table 11. Percent Clearance Absolute Value of t ratio for Significant Factors

Configuration (# MK18)	% Clearance	S_Pcmm	S_Pd
	Mean	|t ratio|	
1M	0.258	62.87	36.22
2M	0.260	61.82	37.28
3M	0.257	61.74	39.20
4M	0.257	60.50	36.05
5M	0.260	60.92	36.58
6M	0.258	61.80	37.08
7M	0.258	60.59	35.21
8M	0.257	60.42	36.70
9M	0.256	61.32	37.00
10M	0.260	61.97	36.01
12M	0.258	59.83	35.60

Figure 22 plots percent clearance and ACRS against legacy configuration 2a, LCS configuration 3, and all MK18 configurations. As seen in previous graphs ACRS performance increases as MK18 numbers increase with configuration 4M and above showing a greater ACRS than both legacy and LCS configurations. As mentioned earlier percent clearance remains fairly constant over all MK18 configurations, but is still lower than the values seen for legacy and LCS configurations.

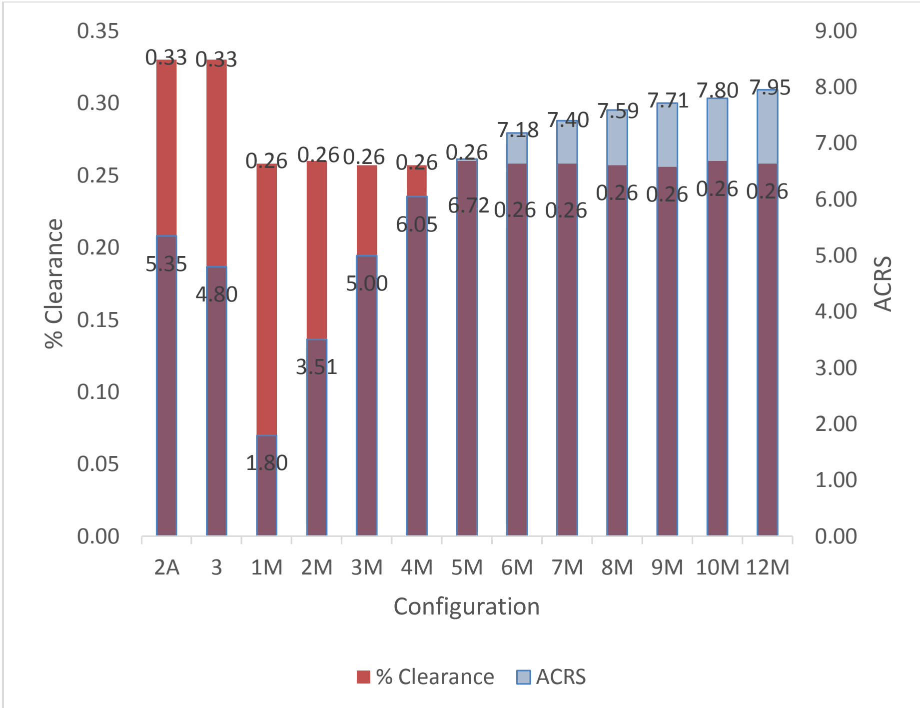

Figure 22. Configuration Performance

From a purely ACRS standpoint four MK18s exceed the performance of both legacy configuration 2a and LCS configuration 3. There does appear to be a point of diminishing returns where ACRS performance gains are not as drastic. The jump from 9M to 10M is not as great as the increase from 1M to 2M.

C. CHAPTER SUMMARY

Using the 38 factors that the previous MIW team (2104) looked at and based the model off of it was determined that 20 of those factors were variable. The remaining factors were held constant. Surface search factors were given as ranges to maintain the unclassified nature of this report. Air neutralization factors were kept the same as previously used since the primary focus of this project is surface search parameters and surface hunt effectiveness of the MK18 Mod 2 versus that of the previously studied RMS. Using the appropriate NOLH spreadsheet for the amount of variable input factors (20) the amount of required model runs, including replication, was determined. Eleven MK18 Mod 2 configurations were investigated, one through 10 and 12 MK18s. The

resulting data was analyzed using JMP™ statistical software and mean ACRS and percent clearance numbers were calculated. Using this data plots were constructed to relate the eleven MK18 Mod 2 configurations with the ACRS and percent clearance values from legacy 2a and LCS configuration 3 determined in the previous MIW project (2014). Also using JMP™ statistical software the top three significant model input factors were determined. This comprised both surface search and air neutralization factors. The top significant input factors for ACRS were found to be surface replenish time (S_Replenish_hr), surface search speed (S_SearchSpeed_kt), surface probability of classifying a non-mine as a non-MILCO (S_Pcnn), and the surface probability of detection (S_Pd). The top significant factors for percent clearance, not including air neutralization factors were surface probability of classifying a mine as a MILCO and surface probability of detection.

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VIII. COST AND RISK ANALYSIS

Included within this study are the comparisons of legacy and future MIW systems, as well as the potential use of the MK18 Mod 2, through an evaluation of cost and risk associated with the systems. An evaluation which relies solely upon performance data alone is not sufficient to provide an accurate reflection of overall effectiveness without the factoring of the costs and operational risk associated with the system. An effective system is one that performs within the expected parameters with minimal risk and at reasonable costs to the acquirer. Providing the acquirer the requisite information regarding cost, performance and risk allows decision makers the ability to accurately evaluate comparative systems for selection based upon a value based analysis. This chapter describes the cost and risk analyses performed by the 2015 MIW team to determine the best value recommendation.

A. COST ANALYSIS

The cost analysis performed by the team was scoped to evaluate only operating and sustainment (O&S) costs. Other life-cycle costs were excluded from study in order to keep this follow on study in line with the previous efforts, and the time and manpower constraints shared with the previous 2014 MIW capstone team.

Within the DOD, acquisitions processes are detailed in DOD Directive (DODD) 5000 series of policy documents, and implemented through the Defense Acquisition Guidebook (DAG) as an authoritative source for the acquisition community for policies and procedures. The guidebook describes the four major categories of programmatic life-cycle costs (Defense Acquistion University 2014) as follows:

- Research and Development – Costs associated with trade studies, technology development, design, fabrication, integration and testing
- Investment – Costs associated with the production and deployment of a capability

- O&S – Costs associated with the operation, maintenance and support of a fielded system including mission costs - those costs and expenditures to support a baseline system or task unit on an hourly cost basis
- Disposal – Costs associated with the demilitarization disposal of military assets

1. Cost Analysis Methodology

The O&S costs referenced within this study for legacy assets were obtained from the 2014 MIW capstone team's report in order for the data to remain consistent. The original source of the cost information for the legacy systems evaluated was the Navy Visibility and Management of Operating and Support Costs (VAMOSC) management information system. The VAMOSC system, available to U.S. government personnel, collects and provides reporting of historical O&S costs data for the Navy and Marine Corps weapon systems. Available cost information was supplemented with current inputs for the MK18 Mod 2 obtained by the 2015 MIW team through SME feedback and research, with a focus on being consistent with the study's objective of evaluating the hunt effectiveness of the MK18 Mod 2 alternative solution. Cost data included in this study relies on estimating the O&S costs associated with supporting the MIW mission. In the case of the baseline MCM 1, it is dedicated to the MIW mission and the VAMOSC data presented in this study accurately reflects the annual costs. For the future MIW alternatives, the LCS with planned mission packages and the alternative MK18 Mod 2, the platform supports many objectives of which MIW is one package. Therefore, although care was taken to provide accurate cost estimates of annual O&S costs based upon SME and stakeholder inputs, the actual costs of the MIW mission may vary from the estimates included in this study due to such factors as time spent dedicated to performing the MIW mission, time spent switching from one MP to another, and the impact of new mission requirements. To refine the accuracy of the study, comparison data based upon the hourly cost of each MIW mission was introduced as the manner to equate costs between the disparate systems, as the model collects data for the time spent on performing each task of the mission in hourly units.

2. Hourly O&S Cost Estimates for MIW Systems

Cost data for each evaluated platform, legacy MCM 1, the CH-53E operating off of the LHD, LCS variant 1 (Freedom), and LCS variant 2 (Independence) with respective associated airborne assets of MH53 and with LCS variants the MH60, was obtained through the VAMOSC database tool as CY15 dollars for comparison. The yearly O&S cost estimations were decomposed, through similar manner as the MIW 2014 to remain consistent, into hourly rates for the shipboard assets by dividing the total yearly O&S cost by the number of hours in a year, 8760. Each asset's operational costs were also broken down into several subcategories to include manpower, energy, maintenance and other to include those costs not included in another category but which still contributes to the operational cost of the asset such as training. The cost data in CY15 million dollar units for the ship assets are included in Appendix C – Table 18 through Table 28. Costs associated with the operation of the MK18 Mod 2 as a MIW search asset through RHIB deployment were obtained through data provided by the MK18 evaluation team of SSC PAC and verified by operational representatives from N95. Manpower to support the operation of the MK18 Mod 2 is included within the operational costs of the RHIB and LCS manning.

Airborne asset hourly calculations also started with the yearly O & S costs but differed from the shipboard values due to additional costs associated with flight hours and the type and location of the maintenance required. The costs associated with organizational and intermediate maintenance, those activities which can be accomplished within or near the deployed activity, were attributed to flight hours. Depot maintenance activities, those tasks which require specialized skills, materiel or facilities performed off-site from the task, were calculated using annual hours. Cost data in CY15 million dollar units are contained within Appendix C – Table 29 through Table 38.

3. Neutralizer O&S Cost Analysis

The cost of neutralizers obtained from SME feedback during the MIW 2014 research was carried through to this study for consistency as the focus of this study was to evaluate the effectiveness of the MK18 Mod 2 as a search asset. The MK18 does not

have the ability to perform the neutralization aspects of the mission, operational commanders would need to employ current or alternate means of neutralization for MIW mission completeness. An assumption that the continued use of the current neutralization approaches of the LCS would be implemented in the short term. The costs associated with the current neutralization from an LCS platform using a MH-60 helicopter and Archerfish neutralizer were applied to the configurations containing the MK18 Mod 2. Data separating the MH-60 O&S costs in relation to the type of maintenance that occur annually for an airborne asset are contained in Appendix C – Table 26 and Table 27. The data for the neutralization systems used in the comparative systems are contained in Table 28. Cost data of the neutralization systems was derived using triangle distributions and runs of 1000 Monte Carlo simulations, since the data provided was linear in nature the resulting simulations provided calculations for expected cost very close to a point estimate of the average of all costs entered. If greater granularity is sought in comparison between the legacy, current LCS and the use of the MK18 Mod 2 as an alternative search asset, a larger sample size of mission costs should be obtained for use as the representative sample size.

4. Scenario Cost Estimates

Estimates for each scenario were calculated from the requisite data contained in the tables above in combination with the resulting model output factors of number of neutralizers used, total mission time and flight time(s) contained in Chapter VII. Using the formula for Total Estimated Cost derived by the 2014 MIW team below, the mission cost of using the MK18 Mod 2 in various quantities were calculated for comparison to the other mission configurations.

$$
\begin{aligned}
&Total\ Estimated\ Cost \\
&\quad = Total\ Mission\ Hours * \left(\frac{Ship\ O\&S}{Annual\ Hours} + \frac{Helicopter\ O\&S}{Annual\ Hours}\right) \\
&\quad + Mission\ Flight\ Hours\left(\frac{Helicopter\ O\&S}{Flight\ Hours}\right) \\
&\quad + Number\ of\ Surface\ Neutralizers * Surface\ Neutralizer\ Cost \\
&\quad + Number\ of\ Airborne\ Netrualizers * Airborne\ Neutralizer\ Cost
\end{aligned}
$$

A separate calculation sheet was derived for each combination of LCS variant and MK18 Mod 2 to account for the differentiation of O&S costs associated with the ship's operation. All other MIW mission functions of the platforms were assumed to be of equal time, cost and effectiveness for this study. Representative samples for what was shown to be the most effective region using four and eight MK18 Mod 2s are included for clarity in Table 12 and Table 13. The Total Estimated Costs for the mission of each variation is included in Appendix C – Table 29 through Table 38 with an isolation of the estimated cost of performing the search aspect of the mission with MK18 for comparison.

Table 12. Baseline Costs (4 MK18 Mod 2)

4 MK18 Mod2 BASELINE & HUNT Cost										
Configuration (4 MK18 Mod2)	Average Mission Time (hours)	Average Flight Time (hours)	Average # Surface Neutralizers	Average # Airborne Neutralizers	Total Ship O&S Cost (CY15$M)	Total MK18 Mod2 O&S Cost (CY15$M)	Total Helicopter O&S Cost (CY15$M)	Total Neutralizer Cost (CY15$M)	Total Estimated Cost (CY15$M)	Total Estimated Hunt Cost (CY15$M)
1A	574.31	72.26	48.56	0.00	11.56	0.00	2.06	0.50	14.12	11.56
1B	578.81	72.26	100.45	0.00	11.65	0.00	2.06	5.95	19.66	11.65
2A	469.71	124.66	36.40	32.78	9.45	0.00	3.33	2.16	14.94	11.11
2B	473.58	124.47	74.49	32.62	9.53	0.00	3.32	6.35	19.20	11.19
3 (LCS 1)	528.10	235.85	0.00	128.38	1.93	0.00	1.67	7.79	11.39	3.60
3 (LCS 2)	528.10	235.85	0.00	128.38	1.43	0.00	1.67	7.79	10.89	3.10
LCS1 w/MK18 Mod2	412.97	235.34	0.00	137.38	1.51	1.87	1.64	8.34	13.36	3.38
LCS2 w/MK18 Mod2	412.97	235.34	0.00	137.38	1.12	1.87	1.64	8.34	12.97	2.99

Table 13. Baseline Costs (8 MK18 Mod 2)

8 MK18 Mod2 BASELINE & HUNT Cost										
Configuration (4 MK18 Mod2)	Average Mission Time (hours)	Average Flight Time (hours)	Average # Surface Neutralizers	Average # Airborne Neutralizers	Total Ship O&S Cost (CY15$M)	Total MK18 Mod2 O&S Cost (CY15$M)	Total Helicopter O&S Cost (CY15$M)	Total Neutralizer Cost (CY15$M)	Total Estimated Cost (CY15$M)	Total Estimated Hunt Cost (CY15$M)
1A	574.31	72.26	48.56	0.00	11.56	0.00	2.06	0.50	14.12	11.56
1B	578.81	72.26	100.45	0.00	11.65	0.00	2.06	5.95	19.66	11.65
2A	469.71	124.66	36.40	32.78	9.45	0.00	3.33	2.16	14.94	11.11
2B	473.58	124.47	74.49	32.62	9.53	0.00	3.32	6.35	19.20	11.19
3 (LCS 1)	528.10	235.85	0.00	128.38	1.93	0.00	1.67	7.79	11.39	3.60
3 (LCS 2)	528.10	235.85	0.00	128.38	1.43	0.00	1.67	7.79	10.89	3.10
LCS1 w/MK18 Mod2	333.48	223.73	0.00	137.27	1.22	3.74	1.55	8.33	14.84	4.96
LCS2 w/MK18 Mod2	333.48	223.73	0.00	137.27	0.90	3.74	1.55	8.33	14.52	4.64

As with the results of the 2014 MIW team, the overall mission costs of the LCS variants consistently demonstrates the lowest mission costs in comparison to the legacy configurations. Among the LCS variants, the LCS 2 (Independence) maintains the lowest overall mission costs but the cost of the neutralization from all LCS configurations is also substantially higher than the legacy configurations as a result of the LCS variants reliance on airborne neutralizers. If alternative means of providing a surface neutralization method in conjunction with the search capabilities of the MK18 Mod 2 were to be implemented, the significant cost reductions provided by the MK18 Mod 2 as a search asset could allow for the implementation of multiple devices to further increase the confidence level in identifying mines and non-mines. Such a reduction in identification time and cost, at equal or greater confidence than currently modeled, would allow operational commanders the opportunity to realize a reduction in the number of neutralizers expended thereby further increasing the operational effectiveness of the MIW mission. This excursion provides areas of interest for future studies to examine the potential of designating the MIW mission among multiple platforms equipped with MK18 Mod 2 and alternate neutralization methods. The cost data results are based upon point estimates derived from limited cost information obtained through VAMOSC and SME feedback, a larger sample size would be desirable to provide proper probability distributions. The full collection of results based upon derived point estimates is contained in Appendix C Table 18 through Table 28.

Further research into the probabilistic cost distributions is warranted for estimation of the number of MK18 Mod 2 to determine a predictive formula for the optimal ACRS to cost ratios under the ideal conditions presented in the model. Metrics for establishing the baseline performance versus cost were calculated by dividing the configurations modeled ACRS by the cost, with the results graphically displayed are contained in Appendix C - Figure 42 through Figure 61 for each configuration and combination of MK18 Mod 2 with baseline and normalized performance displayed. Representative graphics (Figure 23 through Figure 26) for the use of four and eight MK18 Mod 2s as the search asset are displayed below to illustrate the relative ACRS to mission cost and normalized percent clearance effectiveness of the MK18 Mod 2 compared to the legacy and current MCM deployments.

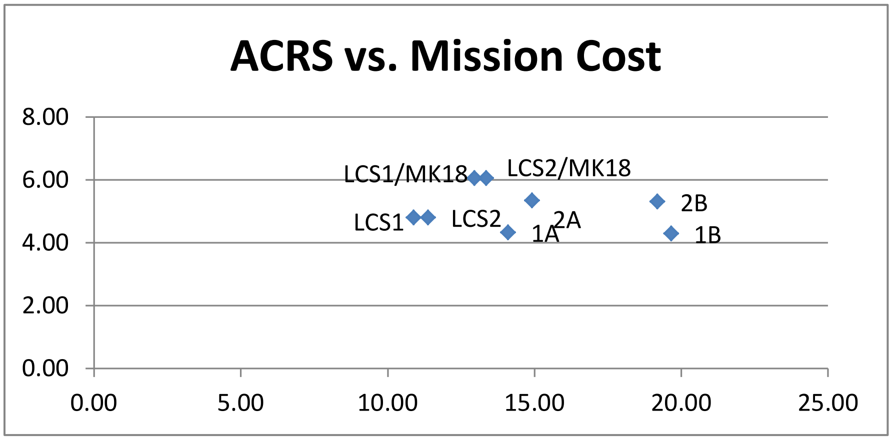

Figure 23. ACRS Baseline vs. Cost (4 MK18 Mod 2)

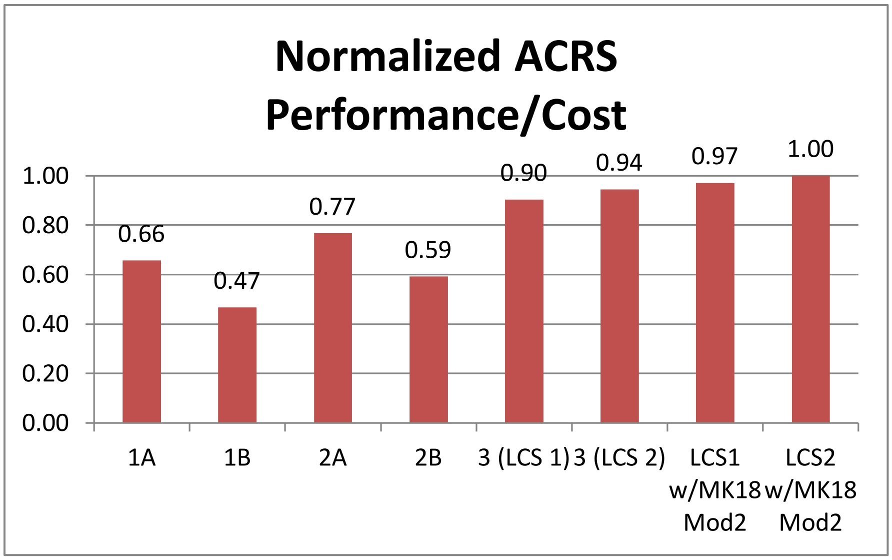

Figure 24. Normalized ACRS Baseline vs. Cost (4 MK18 Mod 2)

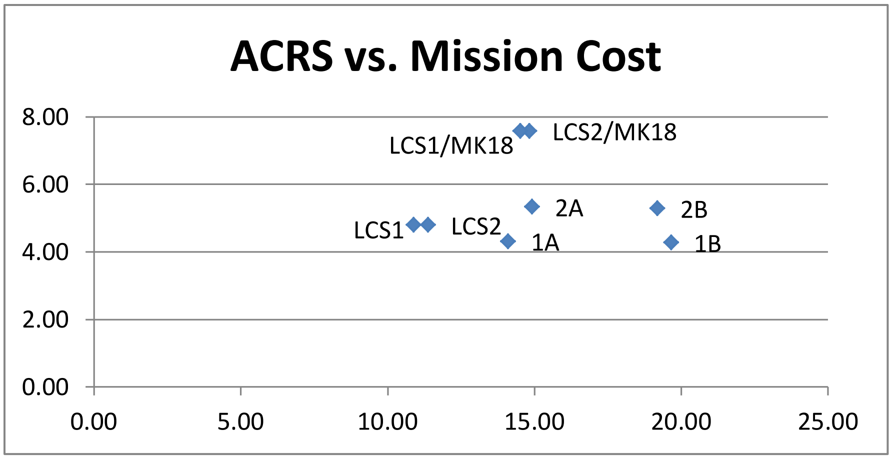

Figure 25. ACRS Baseline vs. Cost (8 MK18 Mod 2)

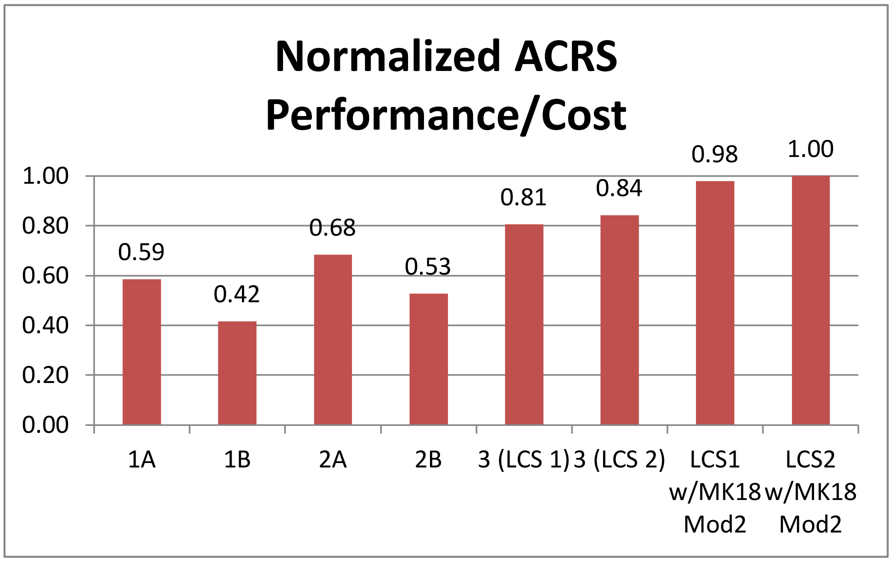

Figure 26. Normalized ACRS Baseline vs. Cost (8 MK18 Mod 2)

The results of ACRS performance when normalized indicate that the MK18 Mod 2 equals the search effectiveness of the programmed LCS MCM mission package when four devices are deployed using two RHIBs, for which the current configuration of the LCS is capable of hosting. This effectiveness is obtained within the model using only one MH-60 helicopter for neutralization, as an excursion removal of this airborne assets neutralization function was performed to investigate only hunt aspect of the mission.

Using the same metrics as the prior calculations, minus the airborne costs and times it was determined that at this same value of four MK18 Mod 2 devices performing the search function it became superior to the currently deployed option. While a brief excursion in this effort was performed to support the team's hypothesis of the limiting factor being the MH-60, the results for the representative selection of four and eight MK18 Mod 2s are shown in Figure 27 through Figure 28 indicated the potential as a viable search asset when paired with either a more effective neutralization system or equipped with better detection and discrimination characteristics. An alternate neutralization system could also be deployed from alternate platforms as well to satisfy portions of the MIW mission more effectively. The full collection of results of the excursion is contained in Appendix C Figure 62 through Figure 71.

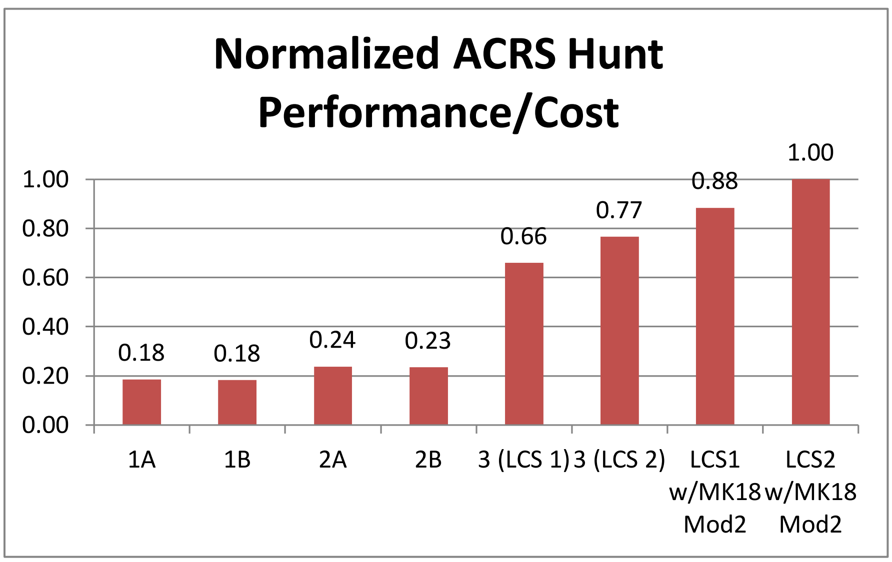

Figure 27. Normalized ACRS Hunt vs. Mission Cost (4 MK18 Mod 2)

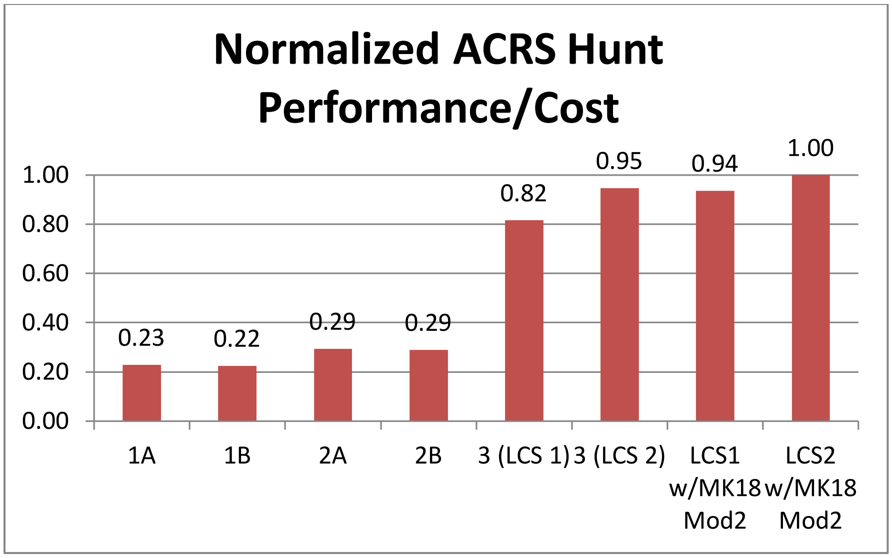

Figure 28. Normalized ACRS Hunt vs. Mission Cost (8 MK18 Mod 2)

The data indicates that within the LCS MIW mission package, a limiting factor in overall effectiveness may be the reliance on airborne neutralization provided by the MH60 shared among all of the LCS configurations modeled or the lower Pd and Pc variables modeled for the MK18 Mod 2. Given that the LCS variants have lower O&S costs as provided to the team, the slightly broader range of the probability of detection of the LCS with the MK18 Mod 2 was not of consequence once the number of MK18 Mod 2 performing the search portion of the mission exceeded three devices operating simultaneously.

While the data provided above support the addition of the MK18 Mod 2 as a search asset within the MIW mission, to effectively compare the results of the prior 2014 MIW capstone report, as shared with the 2015 MIW team through interactions with stakeholders and SMEs, the most readily accepted metric by the community is mission effectiveness as measured through percent clearance. While the MK18 Mod 2 does not perform any of the clearance functions, as mentioned in the previous discussions on searching, effective clearance is directly related to the reliable detection and identification of mines as mines, and elimination as MILCO, which due to their uncertain nature could potentially waste neutralizers. Therefore, the confidence an operational commander can have about the information provided about the subject minefield is paramount to effectively clearing the area for safe transit or operations. The information presented in

Figure 29 through Figure 30 show the normalized results with the inclusion of the neutralization into the overall mission costs when using the modeled MIW packages in deployments utilizing four and eight MK18 Mod 2s as the search asset for comparison. The full analysis for all modeled configurations is contained within Appendix C – Figure 72 through Figure 81.

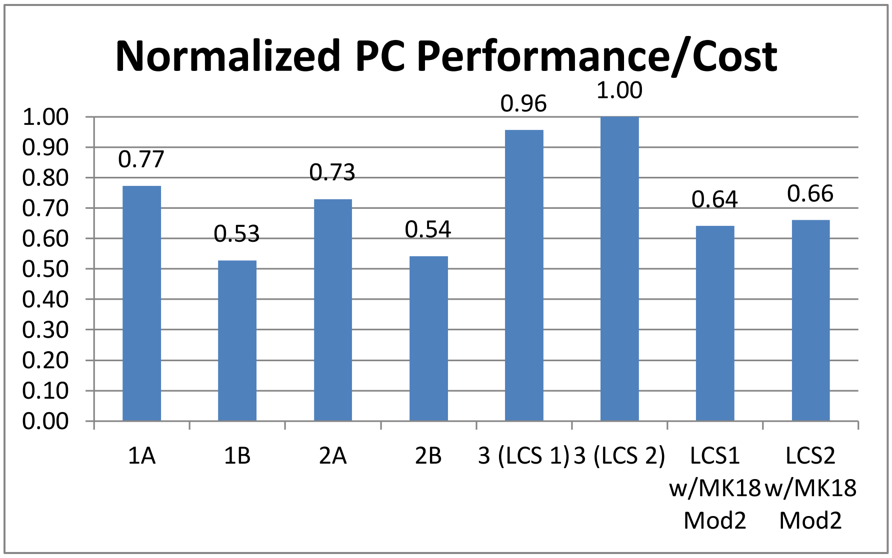

Figure 29. Normalized % Clearance vs. Mission Cost (4 MK18 Mod 2)

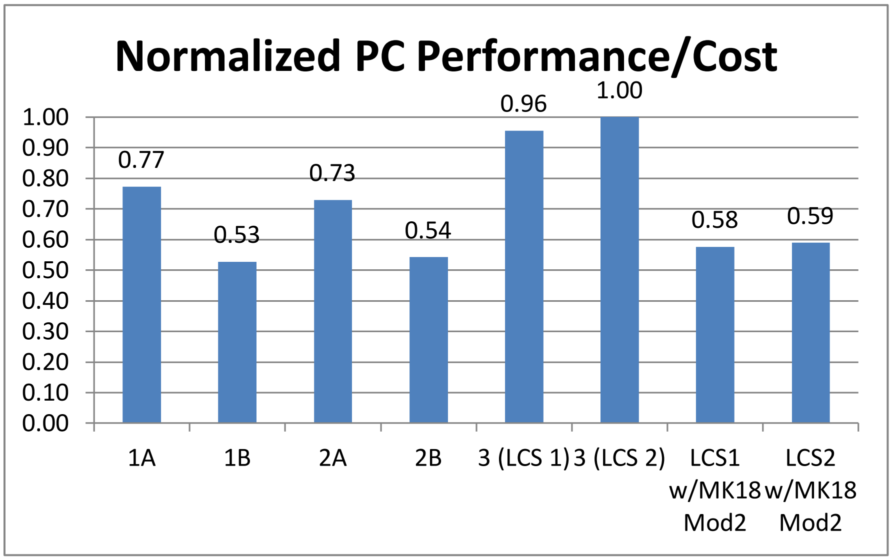

Figure 30. Normalized % Clearance vs. Mission Cost (8 MK18 Mod 2)

As shown in the above graphical representations of the normalized percent clearance to total mission cost, the LCS MIW search alternative utilizing the MK18 Mod 2 provides mission package with the most cost effective solution modeled. These results confirm with the earlier results of the isolation of the search function in which the models suggested the MK18 Mod 2 package as the most cost effective in that area. Although the two LCS packages modeled utilize the same neutralization method, the MH60 and Archerfish neutralizer, the supporting cost data indicates the number of neutralizers expended and the additional cost of the MK18 Mod 2 and RHIB do not adversely affect the overall mission effectiveness when compared with the current LCS MIW package. As indicated earlier, the probability of detection provided and used in this study was of a broader range than the devices contained in the prior year's study suggesting that if the probability were raised to values consistent with the current package the associated overall mission costs could also result in realizing a corresponding reduction.

B. RISK ANALYSIS

A formal risk analysis was not performed in this study due to time and resource constraints, although a cursory evaluation was instituted for the employment of the MK18 Mod 2 only. The risks identified in the 2014 MIW study remain relevant to this study and have been applied to the MK18 Mod 2 deployment as well. The MK18 Mod 2s use as presented in this model assumed that the devices would be released and recovered outside of the actual minefield with transit to and from the host ship to the mission area via the RHIB. Employment of the devices in this manner is in line with the goal of removing the warfighter from the minefield to reduce risk to an acceptable level or below. Since risk is a major contributor to how effective a solution is, particularly within a military scenario, an in-depth analysis of employment of the MK18 Mod 2 warrants additional study for determination of the level of risk implementing the search aspect of the MIW mission may be incurred.

1. Risk Assessment Methodology

The identification and management of risk is necessary in any DOD program and is performed in a methodical manner as prescribed by the Under Secretary of Defense

(USD) Acquisition, Technology and Logistics (AT&L). "Risk management is the overarching process that encompasses identification, analysis, mitigation planning, mitigation plan implementation and tracking" (Department of Defense 2006, 1). Risk is comprised of three primary components:

- a future root cause, which if addressed can eliminate, reduce or prevent an occurrence
- a probability of occurrence
- a consequence or effect upon occurrence

Due to the scope of this study only the factors of identification, analysis and mitigation planning were conducted. These efforts were also limited to only the risk associated with the MK18 Mod 2 as a search asset.

Identification of the risks for the MK18 Mod 2 was facilitated through the literature reviews, stakeholder and SME inputs. Risks are events that have not occurred yet, but may impact cost, schedule or performance of a system; therefore, when evaluating the risks associated with the use of the MK18, only those items which have not yet been realized were considered. This evaluation was also a cursory look into the risks associated with the use of the MK18 Mod 2 and is not all inclusive of all potential risks in operation.

The analysis risks identified follows in the process, with the objective of this phase the development of analytical support for the decisions for estimates of likelihood and consequence of each identified risk. A mapping of the established levels of likelihood corresponding to probability of occurrence was obtained from the USD/AT&L Risk Management Guidebook, Sixth Edition and is included for reference in Table 14 and Table 15.

Table 14. Levels of Likelihood Criteria (source: USD/AT&L, 2006)

Level	Likelihood	Probability of Occurrence
1	Not Likely	~10%
2	Low Likelihood	~30%
3	Likely	~50%
4	Highly Likely	~70%
5	Near Certainty	~90%

Table 15. Levels of Consequence Criteria (source: USD/AT&L, 2006)

Level	Technical Performance
1	Minimal or no consequence to technical performance
2	Minor reduction in technical performance or supportability, can be tolerated with little or no impact on program objectives
3	Moderate reduction in technical performance or supportability with limited impact on program objectives
4	Significant degradation in technical performance or major shortfall in supportability, may jeopardize program success
5	Severe degradation in technical performance: cannot meet KPP or key technical/supportability threshold; will jeopardize program success

Plots of the likelihood and consequence are regularly plotted on a “Risk Cube” using a scale of 1–5, providing a two dimensional representation of the intersection of likelihood and consequence. A sample Risk Cube is shown in Figure 31.

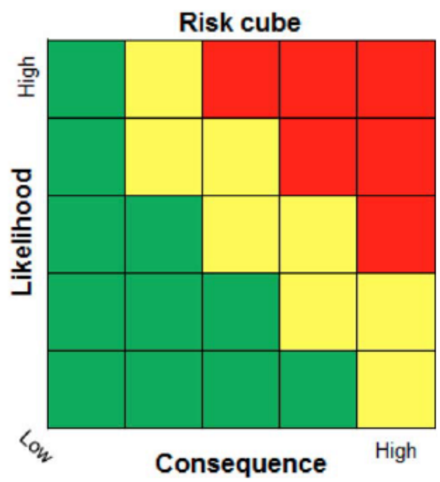

Figure 31. Sample Risk Cube (source: USD/AT&L Risk Management Guidebook, 2006)

Similar to the identification of the risks, estimation of the likelihood and consequences associated with the risks were obtained through literature reviews, interactions with stakeholders, SMEs and some input learned from evaluation of the M&S performed during this study.

To conclude the limited risk assessment for this project was the development of mitigation plans to address the risk in the event of occurrence. Risk mitigation hopes to create an alternative approach in advance which may be implemented when the acceptable risk level is realized. Mitigation can include all or some of the behaviors listed below:

- Avoidance – the root cause of the risk is eliminated.
- Controlling – the root cause of the risk is managed to avoid occurrence.
- Transference – the responsibility of the root cause of the risk is transferred to another party.
- Assumption – the risk is accepted by management.

The risk mitigation suggestions presented in this study have been developed by the 2015 MIW through information obtained during the course of this evaluation.

2. MK18 Mod 2 Risk Assessment

A summary of the risks identified with the use of the MK18 Mod 2, along with proposed mitigation strategies are contained in Figure 32. These risks address the technical system risks and do not cover costs or schedule. A detailed explanation of the

risk, likelihood, consequence and mitigation strategy follow to provide greater detail of the proposal.

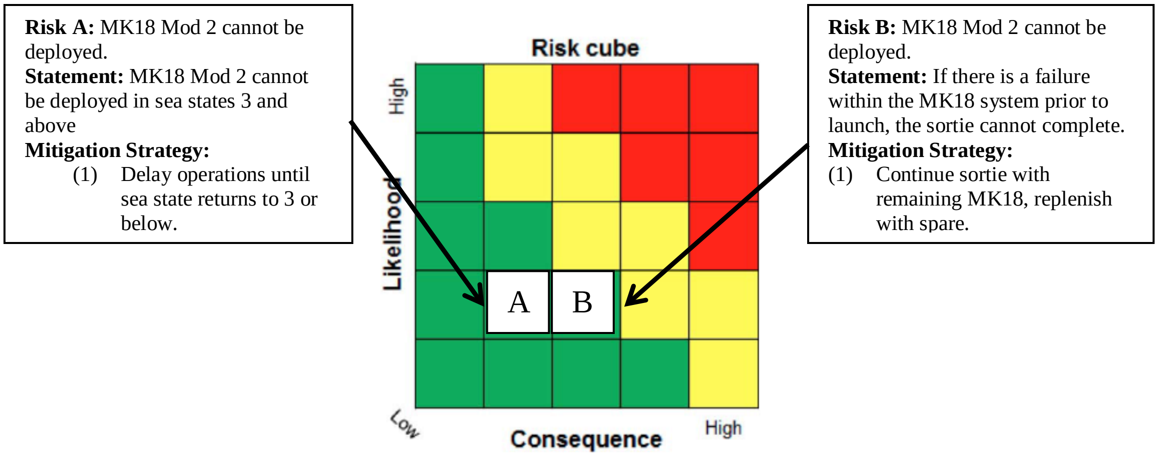

Figure 32. Risk Summary for MK18 Mod 2 (adapted from Frank et al. 2014)

The risks associated with deploying the MK18 Mod 2 as a search asset are:

- Risk A: Sea state at three or above.
    - Risk Statement: If the sea state is determined to be at three or above, the MK18 Mod 2 cannot be relied upon to remain on track and operate in a predictable manner.
    - Likelihood: 2
        - **Rationale:** Average sea state in the Persian gulf is three and below 75% of the time (Bulton 2007)
    - Consequence: 2
        - **Rationale:** In sea states above three nearly all other MIW assets become less reliable in probability of detection and would also incur the need for re-identification of objects to currents.
- Risk B: MK18 Mod 2 cannot be deployed.
    - Risk Statement: If the MK18 Mod 2 malfunctions after transit operations have begun, the sortie for that device must be abandoned until a replacement is deployed.
    - Likelihood: 2
        - **Rationale:** Notional data provided by MK18 Mod 2 SME based upon operational experience rated the reliability high, although normal maintenance is required.
    - Consequence: 3
        - **Rationale:** If a MK18 Mod 2 were to fail, due to the preprogramming of the search area the area which the device would have searched during the planned sortie would have to be searched by an alternate device.

C. COST AND RISK CONCLUSIONS

Our study has concluded that the MK18 Mod 2 is an effective alternative or additional search asset to the LCS MIW package, current and legacy MIW methods when implemented with between four and eight devices performing the search function. Using the cost estimates for the analysis, based upon the data provided variant 2 of the LCS with the MK18 Mod 2 performing the search function has been shown to have the highest ACRS and percent clearance values for the overall mission when the search function is isolated and the highest ACRS regardless of search isolation. Recommendations to improve the neutralization function will increase the effectiveness of the LCS in any configuration, but in particular those implementing the MK18 Mod 2, can raise the overall effectiveness of the LCS MIW variants. While the risk analysis performed in this study was limited to only a cursory view of the potential technical system risks, a major benefit of implementing the MK18 Mod 2 as an alternative search asset is its ability to allow the warfighter to have the MIW mine search function performed by an autonomous vehicle which allows the removal of the need for human entry into the hazardous areas. To further refine the results indicated within this study in regards to both cost and risk a focused study in these areas is a recommendation made by the 2014 MIW team as a logical follow on effort.

IX. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This study set out as a follow-on to the MIW 2014 capstone report in Mine Warfare. The goal of that study was to compare legacy and future MCM capabilities in a single scenario. The MIW 2015 Capstone project set out to do further work that would maintain backwards compatibility with the MIW 2014 project while analyzing new solutions to the MCM problem.

A. SUMMARY

As described in Chapter II, a tailored systems engineering process was utilized in order to conduct the Team MIW 2015 capstone project. This tailored engineering process started with stakeholder analysis, leading to the formulation of a primitive need to compare the MK18 Mod 2 UUV as a search asset in place of the Program of Record (POR) LCS RMS. This primitive need led to the formulation of an effective need, capability need, and finally to the problem statement. The problem statement thus formulated was "The MIW community needs to develop a comprehensive comparative solution to clearly define the gaps between legacy, future, and projected MCM capabilities while providing recommendations involving effectiveness and value for the conduct of sound tradeoff decisions." This statement was used, with stakeholder feedback, to determine requirements that were achievable, realistic, and meaningful to the MIW community.

While formulating the problem statement, extensive literature reviews were conducted allowing Team MIW 2015 to learn about MIW in general and the problems faced over its history. Further consultation with SMEs occurred during the course of this project to answer questions as the team developed a greater understanding of MIW and the needs of the community in developing this study. To focus our search, research questions were developed that guided the team in order to ensure that all necessary information was obtained from experts or literature in a comprehensive fashion that furthered the objectives of this study.

Building from the MIW 2014 study, functional and physical architectures were adapted in order to describe the MK18 Mod 2 UUV and its operation in place of an LCS

RMS. Guided by this, the ARMS model was modified with data describing the MK18s characteristics in varying numbers in order to compare to the top performing legacy and LCS configurations modeled by Team MIW 2014. The results of this data were subjected to cost analysis utilizing the best available cost information in order to determine the cost-effectiveness of each configuration. The conclusions and recommendations are discussed in the next two sub-chapters.

B. CONCLUSIONS

Utilizing the input ranges introduced in Chapter VI, this study found that four MK18s provided a greater ACRS in this scenario than either the legacy or the LCS MCM MP configurations. Summary data for all configurations is presented in Table 16, originally appearing in Chapter VII. Further increases were seen all the way up to 12 MK18s, but the rate of increase decreased significantly and there appear to be diminishing returns. Team MIW 2015 theorizes that this may be due to the 'bottleneck' of utilizing one neutralization asset. This can be seen graphically in Figure 33, also originally appearing in Chapter VII. However, time constraints prevented the team from exploring this potential limitation further and results in a future recommendation.

While percent clearance remained the same for all MK18 configurations modeled, this number was significantly lower than that for the legacy configurations. This is likely due to the differing input ranges provided by SMEs for the MK18s probability of detection and probability of classification of both mines and non-mines. The ranges provided by the SMEs for the MK18 were significantly lower than those provided by the SMEs for the LCS RMS. It is possible that these ranges are not indicative of the relative performance between these two separate search assets as two separate teams provided these ranges that were intended to remain in the unclassified realm. As the MK18 has been utilized operationally in 5th Fleet for several years it likely has significant operational data whereas the LCS RMS has not yet deployed. As a result, these percent clearance numbers are not comparable in practice, and this also resulted in a future recommendation in the next chapter.

Table 16. Summary of Configuration Performance

	ACRS			Percent Clearance		
	Mean	95% Confidence Interval		Mean	95% Confidence Interval	
Configuration		Lower	Upper		Lower	Upper
2A	5.35	5.25	5.45	0.33	0.32	0.34
3	4.80	4.71	4.89	0.33	0.32	0.34
1M	1.80	1.79	1.81	0.26	0.26	0.26
2M	3.51	3.48	3.54	0.26	0.26	0.26
3M	5.00	4.96	5.03	0.26	0.26	0.26
4M	6.05	6.01	6.09	0.26	0.26	0.26
5M	6.72	6.67	6.76	0.26	0.26	0.26
6M	7.18	7.13	7.23	0.26	0.26	0.26
7M	7.40	7.35	7.46	0.26	0.26	0.26
8M	7.59	7.53	7.65	0.26	0.26	0.26
9M	7.71	7.64	0.25	0.26	0.25	0.26
10M	7.80	7.73	7.86	0.26	0.26	0.26
12M	7.95	8.01	8.01	0.26	0.26	0.26

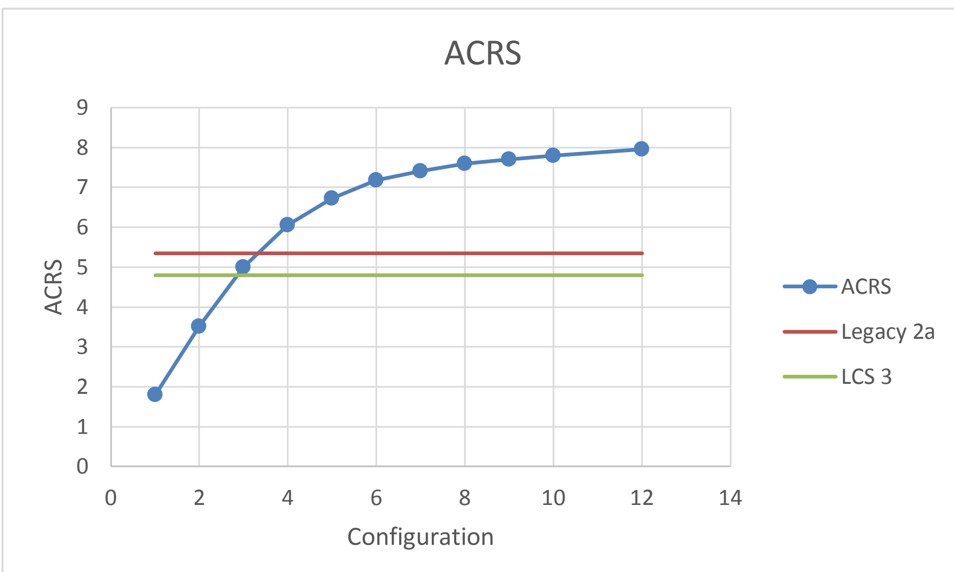

Figure 33. Mean of ACRS vs. Configuration

O&S cost comparisons were conducted between the various configurations, and are summarized in Table 17. As can be seen here, the LCS RMS configurations cost less

per mission on a pure cost basis than any MK18 configuration. However, when cost versus ACRS is considered, four or more MK18s provide equal or greater value than all other legacy or LCS configurations as illustrated in Figure 34.

Table 17. Summary of Cost Data

Configuration	Average Mission Time (hours)	Average Flight Time (hours)	Average # Surface Neutralizers	Average # Airborne Neutralizers	Total Ship O&S Cost (CY15$M)	Total MK18 Mod2 O&S Cost (CY15$M)	Total Helicopter O&S Cost (CY15$M)	Total Neutralizer Cost (CY15$M)	Total Estimated Cost (CY15$M)	Total Estimated Hunt Cost (CY15$M)
1A	574.31	72.26	48.56	0.00	11.56	0.00	2.06	0.50	14.12	11.56
1B	578.81	72.26	100.45	0.00	11.65	0.00	2.06	5.95	19.66	11.65
2A	469.71	124.66	36.40	32.78	9.45	0.00	3.33	2.16	14.94	11.11
2B	473.58	124.47	74.49	32.62	9.53	0.00	3.32	6.35	19.20	11.19
3 (LCS 1)	528.10	235.85	0.00	128.38	1.93	0.00	1.67	7.79	11.39	3.60
3 (LCS 2)	528.10	235.85	0.00	128.38	1.43	0.00	1.67	7.79	10.89	3.10
LCS1 w/1 MK18 Mod2	1415.85	272.70	0.00	137.62	5.18	0.88	2.09	8.35	16.51	6.06
LCS2 w/1 MK18 Mod2	1415.85	272.70	0.00	137.62	3.84	0.88	2.09	8.35	15.17	4.72
LCS1 w/2 MK18 Mod2	721.88	251.07	0.00	137.86	2.64	0.93	1.81	8.37	13.75	3.57
LCS2 w/2 MK18 Mod2	721.88	251.07	0.00	137.86	1.96	0.93	1.81	8.37	13.07	2.89
LCS1 w/3 MK18 Mod2	503.21	241.17	0.00	137.40	1.84	1.82	1.70	8.34	13.70	3.66
LCS2 w/3 MK18 Mod2	503.21	241.17	0.00	137.40	1.36	1.82	1.70	8.34	13.22	3.18
LCS1 w/4 MK18 Mod2	412.97	235.34	0.00	137.38	1.51	1.87	1.64	8.34	13.36	3.38
LCS2 w/4 MK18 Mod2	412.97	235.34	0.00	137.38	1.12	1.87	1.64	8.34	12.97	2.99
LCS1 w/5 MK18 Mod2	372.12	231.83	0.00	137.40	1.36	2.75	1.61	8.34	14.06	4.12
LCS2 w/5 MK18 Mod2	372.12	231.83	0.00	137.40	1.01	2.75	1.61	8.34	13.71	3.76
LCS1 w/6 MK18 Mod2	350.17	228.04	0.00	136.98	1.28	2.80	1.58	8.32	13.98	4.08
LCS2 w/6 MK18 Mod2	350.17	228.04	0.00	136.98	0.95	2.80	1.58	8.32	13.65	3.75
LCS2 w/7 MK18 Mod2	340.62	226.46	0.00	137.54	1.25	3.69	1.57	8.35	14.85	4.93
LCS1 w/7 MK18 Mod2	340.62	226.46	0.00	137.54	0.92	3.69	1.57	8.35	14.53	4.61
LCS1 w/8 MK18 Mod2	333.48	223.73	0.00	137.27	1.22	3.74	1.55	8.33	14.84	4.96
LCS2 w/8 MK18 Mod2	333.48	223.73	0.00	137.27	0.90	3.74	1.55	8.33	14.52	4.64
LCS1 w/9 MK18 Mod2	329.05	222.04	0.00	137.25	1.20	4.62	1.53	8.33	15.69	5.83
LCS2 w/9 MK18 Mod2	329.05	222.04	0.00	137.25	0.89	4.62	1.53	8.33	15.38	5.52
LCS1 w/10 MK18 Mod2	325.51	220.28	0.00	137.34	1.19	4.67	1.52	8.34	15.72	5.86
LCS2 w/10 MK18 Mod2	325.51	220.28	0.00	137.34	0.88	4.67	1.52	8.34	15.42	5.56

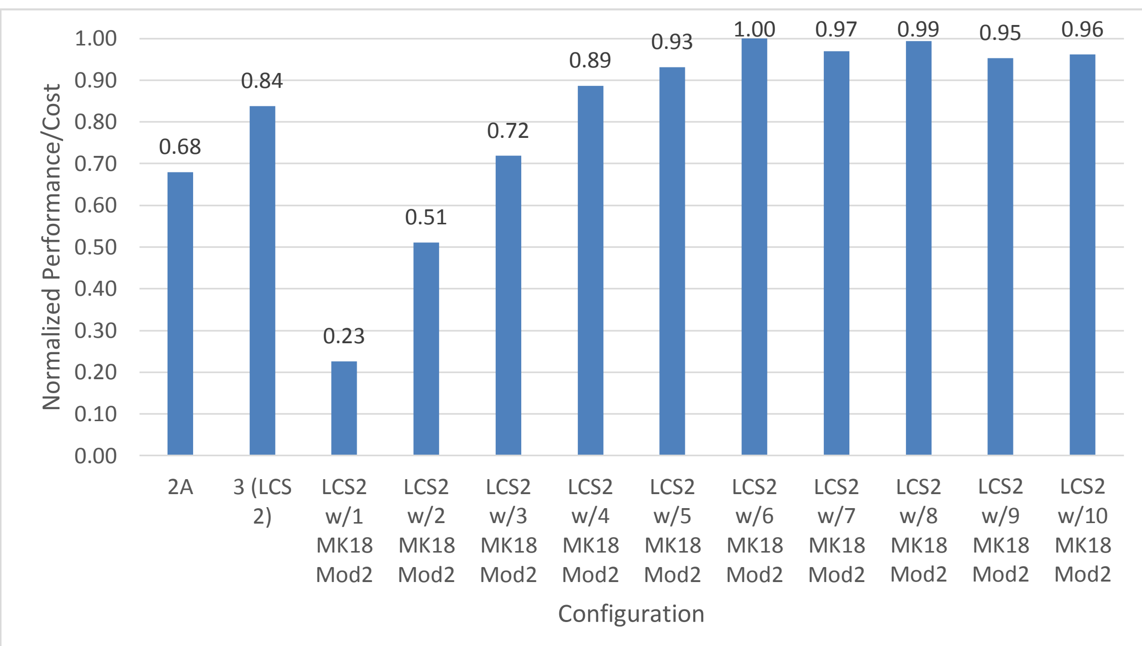

Figure 34. Normalized ACRS Performance/Cost

C. RECOMMENDATIONS FOR FUTURE STUDIES

As future teams endeavor to further MIW, it will be necessary that they conduct their own stakeholder analysis to determine what problems are in greatest need of solution within their work scope and constraints; however, these are areas that Team MIW 2015 believes would provide both adequate work for a future capstone project as well as provide meaningful information to the MIW community.

1. Conduct Classified Analysis

The data utilized in this study consisted of unclassified ranges provided by system SMEs. This information is meant to be representative of the ability of these MCM assets to conduct operations as depicted in this specific operational scenario. As a result, while comparisons can be derived from the data as runs, these comparisons are incomplete and cannot be refined until the actual data is inserted, the model executed, and the outputs reanalyzed. This model should be moved into a classified enclave and populated with the exact data, as determined by SMEs that represent these systems in the given scenario in order to draw direct comparisons of these systems. This includes complete cost data that Team MIW 2015 did not have.

NATO allies also have requirements to meet specific MCM missions and there may be an opportunity to leverage this study to provide comparison data. This would benefit foreign countries as well as our own. This type of comparison would provide the opportunity to analyze their solutions against those of the U.S. Navy in particular scenarios. This could result in a “best of breed” type of systems synthesis that might result in a synergistic combination of allied technologies allowing for a better application of military resources to combat the MCM problem.

2. Alter the Operational Scenario

This model utilized an Operational Scenario as presented in Chapter V. This scenario was based on deep water, bottom mines only, and a fixed 10x10 grid. Future studies should strongly consider altering this scenario in order to compare the removal capabilities between configurations when multiple mine types are considered. This would

result in significant changes to the existing model to accommodate. This would necessitate programming experience on the part of the capstone team.

In addition to differing mine types, adding different field configurations such as would be expected for route clearance would be of significant benefit to the warfighter. Initial mine hunting operations involve clearing a channel to enable access by allied forces and merchant vessels in order to further military ends or ensure the flow of trade goods. These breakthrough scenarios can involve clearance operations up to and including ports which necessitate the consideration of varying bottom depths. Additionally, various search systems have differing sensor configurations that balance different tradeoffs. Simulating these differences could provide insight to the best methods for utilization of differing technologies. Adding further fidelity to the model could also enhance understanding, such as sea state, temperature, bottom types, and salinity.

3. Enhance Understanding of the Current Scenario

The current scenario involving MK18s in place of the LCS RMS offers several avenues for continued study. This study noted apparent limitations or “bottlenecking” when the numbers of MK18s continued to increase. While it was theorized that the single neutralization asset was the limiting factor, this is only a possible explanation, and further investigation is necessary to understand the cause of this decreasing return.

The MK18 is not the only potential expanded search asset for the LCS MCM MP. Unmanned Surface Vehicles (USV) are part of future LCS MCM increments and could offer another alternative to the LCS RMS as a search asset. This investigation has been proposed by the Senate Armed Services Committee (SASC) as well as the MK18 as potential replacements for the LCS RMS (Rear Admiral Rick Williams, USN (Ret), personal comm.). There may be other potential RMS replacements as well that the authors are not aware of.

This study assumed that there would be one RHIB for every two MK18s. This was done to simplify the modeling process. However, the LCS is only capable of carrying two total RHIBs. While this means that the four MK18 scenario, as currently modeled, is

still viable, larger numbers of MK18s would require some other process than that considered here. One potential solution would be multiple trips between RHIBs, each depositing two MK18s, then returning to pick up two more and repeat. At mission conclusion, MK18s would be recovered in a similar fashion. This would require significant changes to the existing model in order to simulate, but this concept of operations is more likely to be utilized and would provide further cost savings for larger numbers of MK18s.

4. Alter MIW Model Underlying Assumptions

The current ARMS model that was initially created by Team MIW 2014 and further utilized by Team MIW 2015 with some modification makes the assumption that the systems modeled begin neutralization operations as soon as initial contacts are found. However, in discussion with SMEs it became apparent that in most SLOC scenarios, this may not be the best option. Most SMEs polled discussed the desire to map the entire field in order to determine the areas of lowest density and clear the necessary channel where mine density is lowest. This change to the model would be significant but also would solve many of the problems that were initially encountered during this capstone project. As this may have more applicability to the warfighter, this future change should be considered.

D. CHAPTER SUMMARY

In this chapter, the work presented in this report was summarized, conclusions were presented, and recommendations for future study were offered. While specific conclusions were given, it is important to remember that this study utilized representative ranges of data in order to remain in the unclassified domain. This study is tentative until a classified analysis can be performed. Results relating to ACRS, heavily dependent on the speed of the search sensor, are more relevant than those relating to the sensors.

More work is needed to move the U.S. Navy further along in combating an age old enemy, the naval mine. Modern technology offers the possibility of combating this threat more effectively than ever before with less risk to personnel. Only with continued effort into research, while properly funded, will this goal be realized. Partnerships with

our allies will assist. As always, the active, reserve, and civilian personnel of the U.S. Navy and her allies stand ready to meet the challenge presented, now and in the future.

APPENDIX A – PROGRAMS AND TOOLS

This appendix provides a description of the programs and tools that were utilized for this capstone study. It includes details of ExtendSim, Innoslate, CORE, Minitab, and JMP™ along with how the 2015 MIW team accessed and utilized each one.

EXTENDSIM – The team utilized the ExtendSim software package. ExtendSim is developed by Imagine That Incorporated and is a software application tool that allows the user to simulate any system by creating logical representations of it. These representations are created using building blocks that enable the user to build their own specialized application model. The building blocks are connected together via graphical user interfaces to create the logical flow of the model as illustrated in Figure 35. When constructing a model, data resides within the parameters of the blocks and in a database.

Figure 35. ExtendSim Logical Flow Example

ExtendSim also has the capability to customize the behavior of blocks with their programming language called ModL. ExtendSim is designed for rapid prototyping so that basic functionality can be achieved quickly and then additional complexity or fidelity can be added as needed, which is facilitated by allowing unlimited hierarchical decomposition to allow the user to produce a modular design with reusable components (Frank et al. 2014). The team accessed this software package from the NPS CloudLab and/or personal licensed copies.

INNOSLATE – The team utilized the Innoslate software package. Innoslate is developed by Spec Innovations and is a software based tool for requirements traceability and architecture views. It is designed to scale to very large projects and allows the team

to coordinate and receive updates regarding project status, database changes, and model maturity within a project dashboard. Innoslate was used to develop the physical and functional diagrams for this project. The team accessed this web based software package from their personal computers.

CORE – The team utilized the CORE software package. CORE is developed by Vitec Corporation and is a model-based system engineering software tool combining modeling language and MBSE methodology. It was developed to serve a systems engineering purpose where by system requirements, behavior, architecture, verification, and validation are pieces that can be decomposed to provide full system information in an organized manner. CORE takes complex issues and organizes the concepts and requirements. It models the behavior of a system and interacts with the concept of operations. It manages requirements and decomposes down to system functionality with complete system behavior analysis, and simulates system performance. CORE also develops and traces system architecture down to subsystems and components while providing traceability from system design to verification and validation plans and procedures. The team accessed this software package from their personal computers.

MINITAB – The team utilized the Minitab software application. Minitab is a tool for statistical data analysis. It allows the user to display the statistic results and other outputs as well as the actual data being used. The team accessed this software package from their personal computers or from the NPS CloudLab.

JMP – The team utilized the JMP software application. JMP is an interactive and visual tool for statistical data analysis very similar to Minitab. The main difference is that the team utilized JMP for a specialized focus on partitioning the output dataset results to calculate the most optimum set of factors for ACRS and % Clearance. The team accessed this software package from their personal computers or from the NPS CloudLab.

APPENDIX B – NAVY MISSIONS

This appendix provides a discussion of the U.S. Navy's assigned missions of sea control, forward presence, power projection, deterrence, maritime security, and humanitarian assistance/disaster relief. It presents these missions as seen from a systems engineering approach using tools such as EFFBDs and functional decompositions.

INTRODUCTION

The U.S. Navy Doctrine Publication 1 (NDP-1) defines six core capabilities of Naval Forces. These are forward presence, deterrence, sea control, power projection, maritime security, and HA/DR (U.S. Navy 2010). These core capabilities are the theoretical basis for everything the Navy does. However, the linking documentation defining the connection between these required capabilities and the actual physical Navy components that perform these missions does not exist (Vego 2008). Naval Warfare Publication 3-15 (NWP) 3–15, *Naval Mine Warfare,* defines Naval Mine Warfare as it currently exists, but ultimately is lacking in its description as there is no higher framework on which it is based (Vego 2008). NWP 3–15 is a good description of what existing MIW missions and capabilities are, and the components that fulfill them, but there is no adjoining framework describing how these missions, capabilities, and resulting components fit into the overall national strategy as defined by the President, Secretary of Defense, and Chairman of the Joint Chiefs of Staff (CJCS).

NAVY MISSIONS

In applying an SE approach to navy missions, dependencies among these capabilities are clearly evident. As defined in NDP-1, these are equal mission areas as shown in Figure 36.

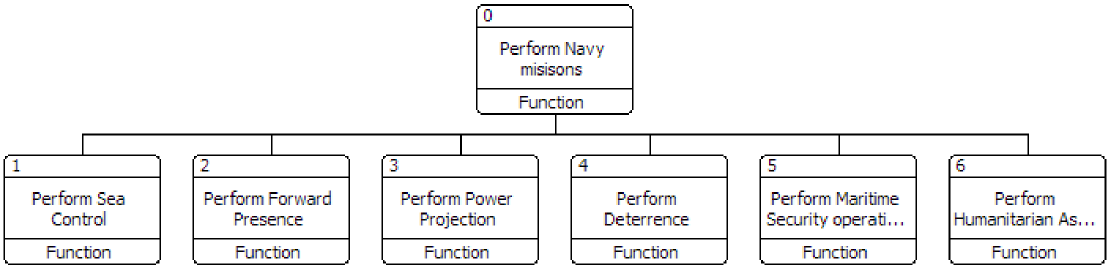

Figure 36. Navy Capabilities

(1) Sea Control

Throughout history, control of the sea has been a precursor to victory in war. Sea control is the essence of sea power and is a necessary ingredient in the successful accomplishment of all naval missions. Naval forces execute sea-control operations to prevent or limit the spread of conflict as well as to prevail in war. Sea control and power projection complement one another. Sea control allows naval forces to close within striking distance to remove landward threats to access, which in turn enhances freedom of action at sea. Freedom of action at sea enables the projection of forces ashore. Sea-control operations are the employment of naval forces, supported by land, air, and other forces as appropriate, in order to achieve military objectives in vital sea areas. Such operations include destruction of enemy naval forces, suppression of enemy sea commerce, protection of vital sea lanes, and establishment of local military superiority in areas of naval operations. (U.S. Navy 2010, 27)

(2) Forward Presence

U.S. naval forces are forward deployed around the clock. These forces support a Combatant Commander's (CCDR's) theater campaign plan. The forward operating posture serves several key functions: it enables familiarity with the operational environment, as well as contributing to an understanding of the capabilities, culture, and behavior patterns of regional actors, and it enables influence. This understanding and influence facilitate more effective responses in the event of crisis. Should peacetime operations transition to war, commanders and commanding officers will have developed their naval forces' environmental and operational understanding and experience to successfully engage in combat operations. Forward presence also allows us to combat terrorism as far from U.S. shores as possible. Where and when applicable, forward-deployed naval forces isolate, capture, or destroy terrorists and their infrastructure, resources, and sanctuaries, preferably in conjunction with coalition partners. (U.S. Navy 2010, 26)

(3) Power Projection

> As a largely sea-based force, the naval team can overcome diplomatic, military, and geographic challenges to access and project power ashore without reliance on ports and airfields in the objective area. In an era of declining access, naval forces play a critical role in projecting U.S. power overseas. Naval forces that are persistently present and combat-ready provide the United States primary forcible entry option, even as they provide the means to respond quickly to other crises. The ability to overcome challenges to access and to project and sustain power ashore is the basis of combat credibility and deterrence capability. (U.S. Navy 2010, 29)

(4) Deterrence

Deterrence is “the prevention from action by fear of the consequences. Deterrence is a state of mind brought about by the existence of a credible threat of unacceptable counteraction” (U.S. Joint Chiefs of Staff 2010, 67).

> The term generally refers to a strategy, in any potential conflict, of being prepared to inflict unacceptable damage on an adversary and making sure the potential adversary is aware of the risk so that the adversary refrains from aggression. U.S. naval forces maintain that core capability and, through employments and capabilities, deter adversaries from aggressive actions on U.S. partners. These naval forces’ capabilities include sea-based nuclear weapons and the forward posturing of credible conventional combat power in key regions, as well as the ability to surge forces tailored to meet emerging crises. (U.S. Navy 2010, 26)

(5) Maritime Security

> Naval forces conduct operations throughout the maritime domain and view the oceans not as an obstacle but as the base of operations and maneuver space, which we either can control for our own use or deny an opponent. Whenever naval forces face an adversary without formidable fleet assets such as carriers, submarines, and larger surface combatants, the seas serve as barriers for naval force defense. As important, though, the seas provide avenues of world trade and military lines of communications for the United States, its allies, and its friends. (U.S. Navy 2010, 29).

(6) Humanitarian Assistance/Disaster Relief (HA/DR)

> The capabilities that allow naval forces to project combat power are also effective at responding to the world’s natural disasters. Operating without reliance on ports and airfields ashore and in possession of organic medical

> support, strategic and tactical lift, logistics support, robust communications capabilities, and premier planning and coordination tools, naval forces are ideally suited for HA/DR, as the vast majority of the world's population lives within a few hundred miles of the seas and oceans. (U.S. Navy 2010, 30)

NAVY MISSIONS AS A CAMPAIGN

Joint Publications (JPs) are the basis for all service level publications. This includes NDP-1. NDP-1 references JP 3–0 to describe the six phases of a campaign.

> JP 3-0, *Joint Operations*, describes six phases of an operation or campaign: shape, deter, seize the initiative, dominate, stabilize, and enable civil authority. While phases are usually conceived and depicted as sequential in nature, as a practical matter there may be considerable overlap and simultaneity among phases. (U.S. Navy 2010, 38)

NDP-1 further ties the six mission areas and their significance to these six campaign phases, setting an expected mission hierarchy. In Figure 37, the six core capabilities are shown on the y-axis, and the six campaign phases are shown on the x-axis. From here, you can see how for phase zero, the predominant required naval capability is maritime security. This then leads into forward presence and deterrence during phase one. Sea control and power projection are the predominant capabilities required for phase three. HA/DR never particularly dominates as a required capability, though in terms of campaign planning it is most likely to occur once the objective action has been completed, in this case phase four. As the campaign comes to an end, maritime security once again dominates returning full circle to phase zero operations. Graphically depicts this arrangement. This also serves to demonstrate how the Navy's missions are not neatly tied to a campaign, but are always utilized in some capacity regardless. It is not the intent here to debate the merits of the Joint Service campaign system, but there are logical shortcomings that cannot be ignored.

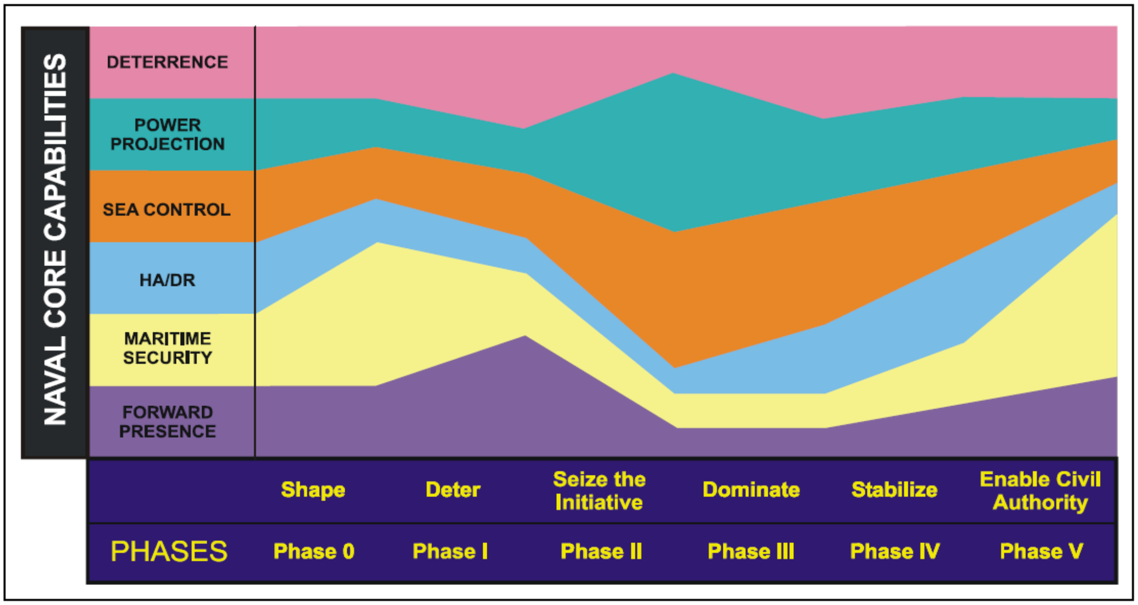

Figure 37. Campaign Phases (source: U.S. Navy 2010)

DEPENDENCIES AMONG U.S. NAVY MISSIONS

As shown in Figure 36, the U.S. Navy core capabilities are described and discussed in some detail, and through this discussion there are a series of dependencies required among them in order for the successful conduct of each mission area. Once these dependencies are diagrammed it will become apparent that the campaign phasing above is in error when applied to Navy missions.

First, as shown in Figure 38, all mission areas require sea control in order for successful implementation. Sea control is necessary for all combatants, whether singly or in groups, in order to safely conduct operations. An Aegis cruiser has complete control of the airspace within its radar range. A battle group with an E-2 Hawkeye airborne not only dominates the airspace but also has detailed knowledge of and the ability to eliminate any surface threat within its radar horizon. A Navy unit does not get underway without some minimal degree of control of its surroundings.

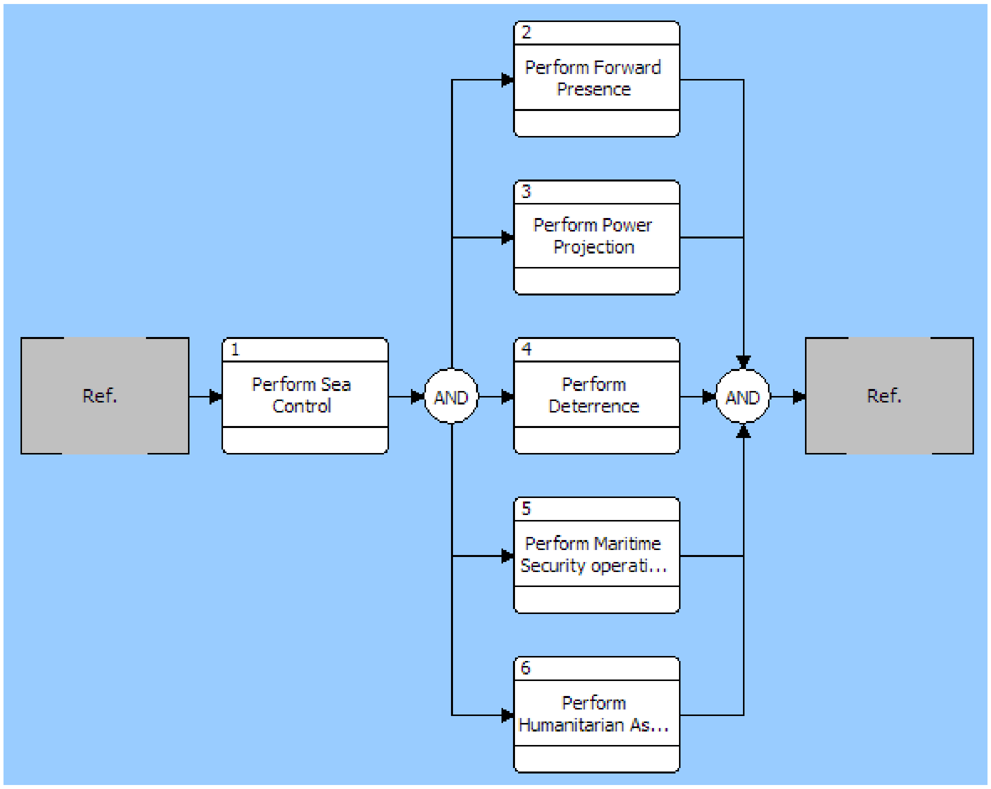

Figure 38. Initial Navy Missions EFFBD

Sea control is not the only dependency to consider. Power projection requires some form of forward presence, as does maritime security and deterrence. We then arrive at the description shown in Figure 39. Consider this in the context of a deploying Carrier Battle Group (CVBG) moving under orders to the Indian Ocean. The battle group gets underway. Immediately upon clearing the piers, the individual units making up the battle group control a large volume including air, sea, land, and space around them. Not only is the battle group aware of its surroundings, but has the capability to perform a large number of desired effects on anything in range. This state continues to exist throughout its transit to the desired operating area south of India.

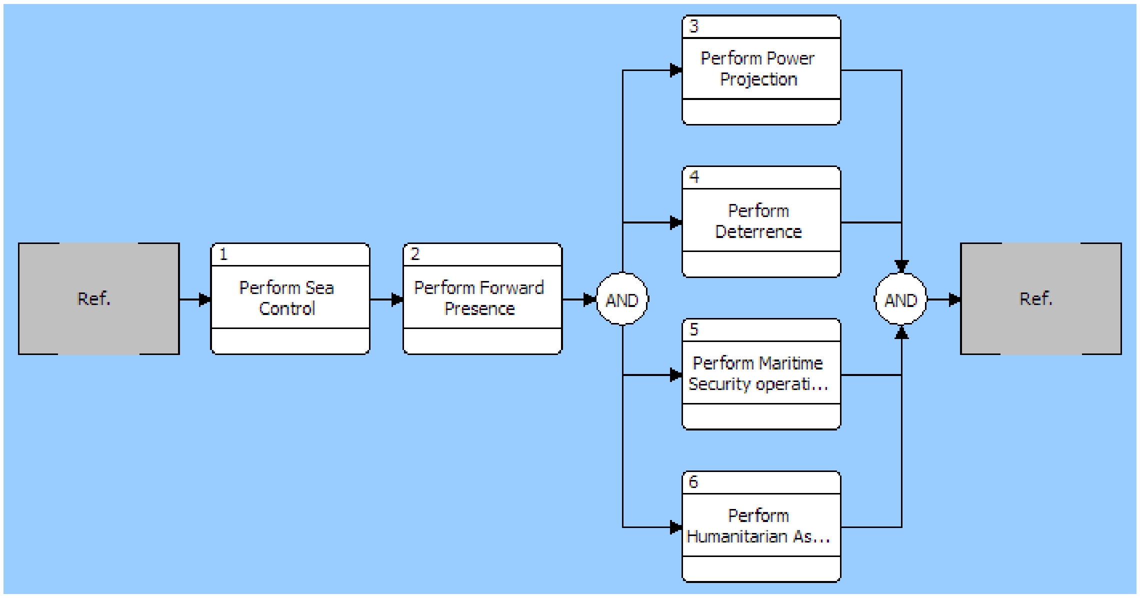

Figure 39. U.S. Navy Missions EFFBD

Once the CVBG has completed transiting to the Indian Ocean, it maintains sea control around the battle group. Due to the battle groups proximity to various foreign countries, forward presence is now established. With this forward presence, any of the four remaining missions can be executed.

These simple arrangements are not meant to be all inclusive, rather this is a brief study meant to demonstrate the need for further work in this area. The U.S. Navy's architectural structure, currently based around current capability and force structure, could benefit greatly from the application of functional analysis in describing a desired future state.

FUNCTIONAL ANALYSIS

Figure 40 shows an as-is functional architecture under the capability area of sea control. As the U.S. Navy is currently organized, it divides into warfare areas that are designed to counter specific threats, as in this example, the primary warfare areas of Anti-Air Warfare (AAW), Anti-Surface Warfare (ASuW), Anti-Submarine Warfare (ASW). The Navy then defines specialty warfare areas of Naval Special Warfare (NSW), MIW, and Cyber Warfare (CYW). This decomposition is a reflection of existing arrangements, but is not typically representative of engineering design.

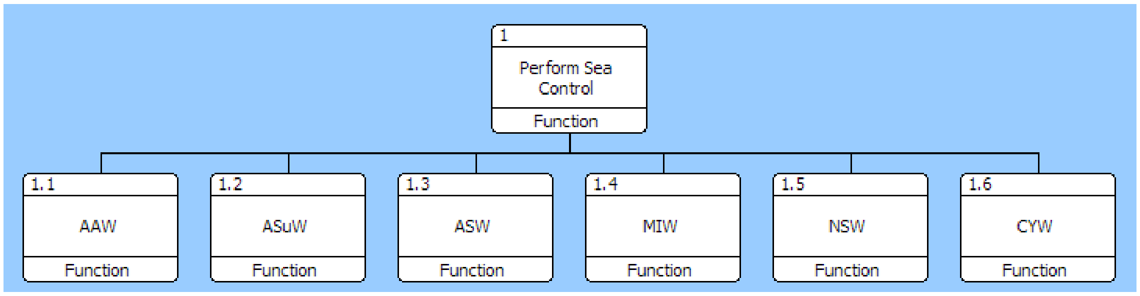

Figure 40. Sea Control Current Functional Decomposition

Systems engineering philosophy requires that a functional decomposition be solution agnostic. Figure 41 demonstrates a functional decomposition representative of systems thinking. This allows for creative solutions to be created that do not rely on existing paradigms. This is not a be-all way of doing, as focus on new and innovative thinking can obscure simpler solutions based on existing systems.

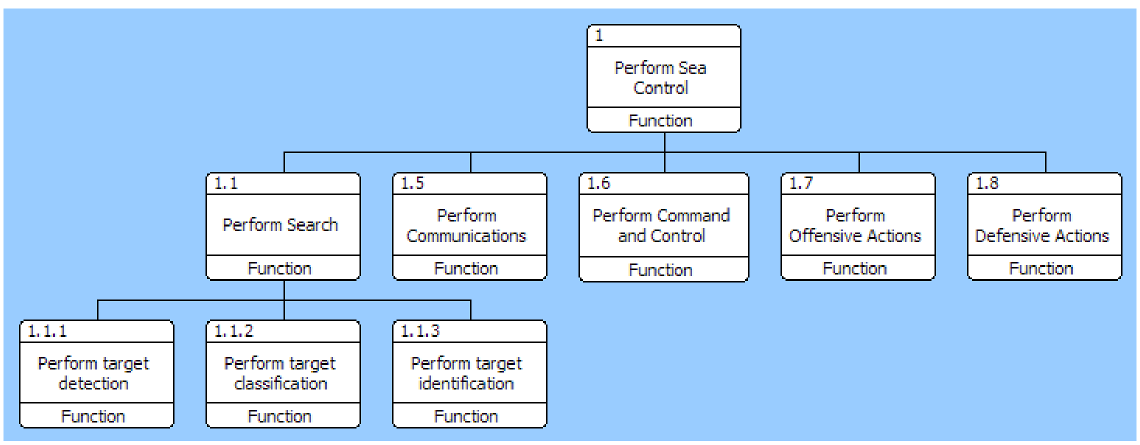

Figure 41. Sea Control Solution Agnostic Decomposition

Figure 41 shows many functions necessary in sea control without specifying how or where they would occur. First, allied forces need to search the area for other contacts. This is further decomposed by detection, classification, and identification activities. Allied forces need to be able to communicate within this area, and perform command and control functions. Finally, the need for offensive and defensive functions are the core of what we think of as sea control, the ability to impose national will.

CONCLUSION

This chapter was written in order to suggest that our current national direction, from the President down to the individual services, could benefit from an engineering functional analysis to determine a more effective structure for future military operations. This starts with clear national objectives that can be further decomposed down to individual military functions allowing for a complete functional to physical component mapping to take place. This ensures that only necessary functions are fulfilled, and clearly defines the order in which functions are necessary for the overall mission, allowing for a more precise allocation of national effort.

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APPENDIX C – COST FIGURES AND TABLES

This appendix includes all of the cost data figures and tables. It provides the detailed results that were not included in Chapter VIII. This appendix begins with the annual O&S costs. It continues with the ACRS baseline, normalized ACRS baseline, normalized ACRS hunt, normalized percent clearance, and baseline cost charts for each of the 10 MK18 Mod 2 modeled scenarios.

Table 18. MCM 1 Annual O&S Cost

Cost Category	MCM 1 Annual O&S Cost[1] (2004-2013, CY15M$)			Average Hourly Cost[2] (CY15$)	Standard Deviation (CY15$)
	Minimum	Average	Maximum		
Manpower	6.85	7.37	7.84	841	48
Energy	0.21	0.30	0.49	34	10
Maintenance	4.21	5.54	8.90	632	170
Other	0.91	1.62	2.24	185	54
Total[3]	12.17	14.82	19.48	1,692	

[1] Based on VAMOSC sample size of 10 years.
[2] Average annual cost divided by 8,760 hours per year.
[3] Total of min, avg, and max years for each cost category. Not an actual annual cost.

Table 19. LHD 1 Annual O&S Cost

Cost Category	LHD 1 Annual O&S Cost[1] (2004-2013, CY15M$)			Average Hourly Cost[2] (CY15$)	Standard Deviation (CY15$)
	Minimum	Average	Maximum		
Manpower	80.05	88.65	92.91	10,120	456
Energy	16.83	23.13	27.51	2,641	376
Maintenance	17.19	31.69	46.26	3,618	978
Other	10.80	17.96	28.82	2,050	593
Total[3]	124.87	161.43	195.50	18,428	

[1] Based on VAMOSC sample size of 10 years.
[2] Average annual cost divided by 8,760 hours per year.
[3] Total of min, avg, and max years for each cost category. Not an actual annual cost.

Table 20. LCS 1 (Freedom) Annual O&S Cost

Cost Category	LCS 1 Annual O&S Cost[1] (2010-2013, CY15M$) Minimum	Average	Maximum	Average Hourly Cost[2] (CY15$)	Standard Deviation (CY15$)
Manpower	8.04	9.52	10.13	1,087	113
Energy	1.38	4.70	9.07	536	367
Maintenance	8.43	15.95	20.02	1,821	587
Other	1.57	1.87	2.26	214	34
Total[3]	19.42	32.04	41.49	3,657	

[1] *Based on VAMOSC sample size of 4 years.*
[2] *Average annual cost divided by 8,760 hours per year.*
[3] *Total of min, avg, and max years for each cost category. Not an actual annual cost.*

Table 21. LCS 2 (Independence) Annual O&S Cost

Cost Category	LCS 2 Annual O&S Cost[1] (2011-2013, CY15M$) Minimum	Average	Maximum	Average Hourly Cost[2] (CY15$)	Standard Deviation (CY15$)
Manpower	9.55	9.68	9.91	1,104	23
Energy	2.00	2.43	2.91	277	52
Maintenance	4.39	10.30	16.76	1,175	708
Other	1.07	1.35	1.64	155	33
Total[3]	17.00	23.75	31.21	2,711	

[1] *Based on VAMOSC sample size of 3 years.*
[2] *Average annual cost divided by 8,760 hours per year.*
[3] *Total of min, avg, and max years for each cost category. Not an actual annual cost.*

Table 22. RHIB Annual O&S Cost

Cost Category	RHIB Annual O&S Cost[1] (2010-2013, CY15M$) Minimum	Average	Maximum	Average (CY15$)	Standard Deviation (CY15$)
Manpower	0.70080	0.78840	0.87600	0.78840	0.00000
Energy	0.00011	0.00011	0.00011	0.00011	0.00000
Maintenance	0.04250	0.04625	0.05000	0.04625	0.00000
Other					
Total[3]	0.74341	0.83476	0.92611	0.83476	

1 Based on SME/N95 input.
[2] *Average annual cost divided by 8,760 hours per year*
[3] *Total of min, avg, and max years for each cost*

Table 23. MK18 Mod 2 Annual O&S Cost

Cost Category	MK18 Mod 2 Annual O&S Cost[1] (2010-2013, CY15M$) Minimum	Average	Maximum	Average Hourly Cost[2] (CY15$)	Standard Deviation (CY15$)
Manpower	0.000000	0.000000	0.000000	0.000000	0.000000
Energy	0.000000	0.000000	0.000000	0.000000	0.000000
Maintenance	0.045000	0.050000	0.055000	0.050000	0.000000
Procurement Cost[4]	0.900000	1.000000	1.100000	1.000000	0.000000
Other					
Total[3]	0.045000	0.050000	0.055000	0.050000	

[1] Based on SME/N95 input.
[2] Average annual cost divided by 8,760 hours per year
[3] Total of min, avg, and max years for each cost
[4] Maintenance costs caluculated at 5% of procurement

Table 24. MH-53 E Annual O&S Cost (Flight Hours)

Cost Category	MH-53 E Annual O&S Cost[1] (2010-2013, CY15M$) Minimum	Average	Maximum	Average Flight Cost/Hour (CY15$)	Standard Deviation (CY15$)
Manpower- Maint	1.68	1.91	2.08	8,598	755
Energy	0.41	0.49	0.56	2,211	313
Maintenance-O	2.96	3.10	3.26	13,921	558
Maintenance-I	0.01	0.07	0.18	299	357
Total[3]	5.06	5.57	6.08	25,029	

[1] Based on VAMOSC sample size of 4 years.
[2] Average annual cost divided by average flight hours per year
[3] Total of min, avg, and max years for each cost category. Not an actual annual cost.

Table 25. MH-53 E Annual O&S Cost (Annual Hours)

Cost Category	MH-53 E Annual O&S Cost[1] (2010-2013, CY15M$)			Average Non-Flight Cost/Hour (CY15$)	Standard Deviation (CY15$)
	Minimum	Average	Maximum		
Manpower- Op	0.96	1.05	1.13	120	8
Manpower-Other	0.56	0.60	0.67	69	6
Maintenance-D	0.68	0.88	1.26	100	30
Other	0.96	1.33	1.69	152	40
Total[3]	3.15	3.86	4.75	440	

[1] Based on VAMOSC sample size of 4 years.
[2] Average annual cost divided by 8,760 hours per year.
[3] Total of min, avg, and max years for each cost category. Not an actual annual cost.

Table 26. MH-60 Annual O&S Cost (Flight Hours)

Cost Category	MH-60 S Annual O&S Cost[1] (2010-2013, CY15M$)			Average Flight Cost/Hour (CY15$)	Standard Deviation (CY15$)
	Minimum	Average	Maximum		
Manpower- Maint	1.03	1.08	1.14	3,134	147
Energy	0.17	0.18	0.19	526	24
Maintenance-O	0.80	0.89	0.98	2,577	277
Maintenance-I	0.10	0.13	0.15	370	65
Total[3]	2.10	2.28	2.46	6606	

[1] Based on VAMOSC sample size of 4 years.
2 Average annual cost divided by average flight hours per yea
[3] Total of min, avg, and max years for each cost category.

Table 27. MH-60 Annual O&S Cost (Annual Hours)

Cost Category	MH-60 S Annual O&S Cost[1] (2010-2013, CY15M$)			Average Non-Flight Cost/Hour (CY15$)	Standard Deviation (CY15$)
	Minimum	Average	Maximum		
Manpower- Op	0.82	0.85	0.88	97	4
Manpower-Other	0.27	0.29	0.30	33	1
Maintenance-D	0.13	0.13	0.14	15	1
Other	0.50	0.52	0.55	59	2
Total[3]	1.72	1.80	1.88	205	

[1] Based on VAMOSC sample size of 4 years.
[2] Average annual cost divided by 8,760 hours per year.
[3] Total of min, avg, and max years for each cost category.

Table 28. Neutralizer Costs

Type Neutralizers	CY15 $ Min Cost	Most Likely	Max Cost	Monte Carlo Output 1st 1,000 Runs	2nd 1,000 Runs	3rd 1,000 Runs	Mean Cost (CY15$)
Archerfish	50000.00	60000.00	70000.00	58044.83	60236.79	63832.30	60704.6
Seafox	50000.00	60000.00	70000.00	59928.68	56308.32	61569.74	59268.9
SLQ-48	9000.00	10000.00	11000.00	9803.93	10786.98	10340.67	10310.5

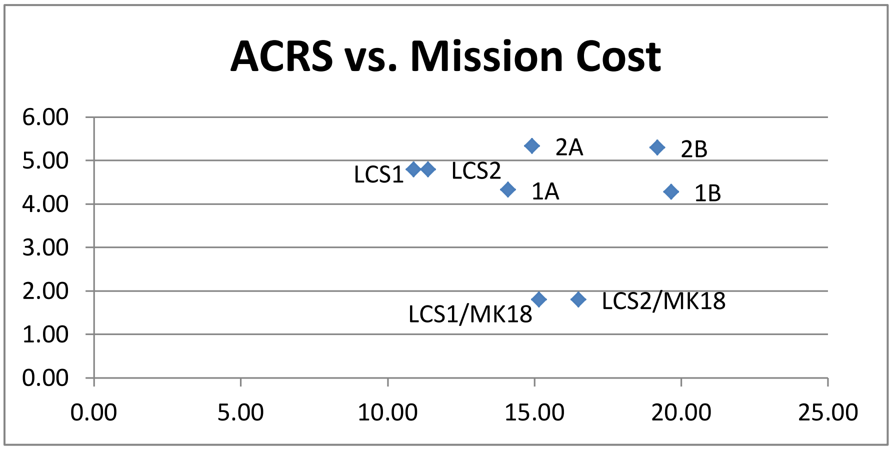

Figure 42. ACRS Baseline vs. Cost (1 MK18 Mod 2)

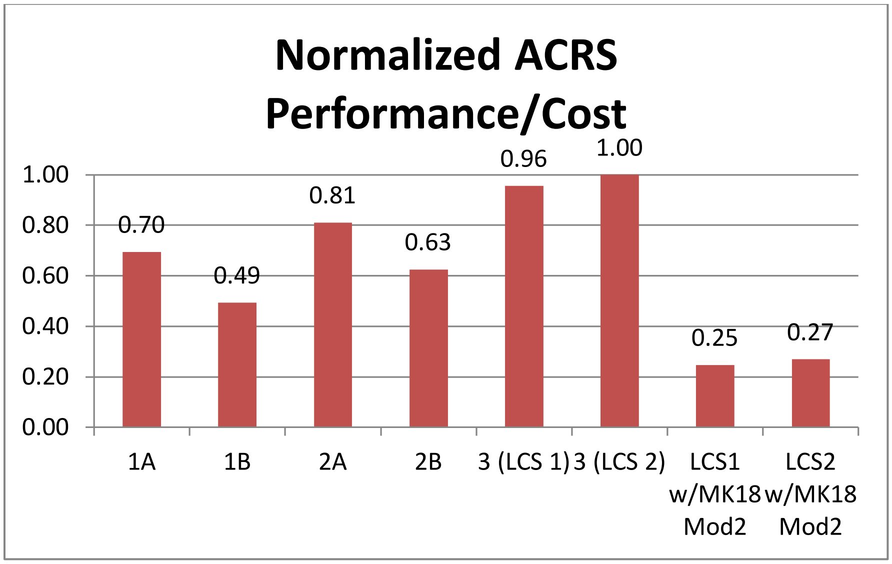

Figure 43. Normalized Baseline vs. Cost (1 MK18 Mod 2)

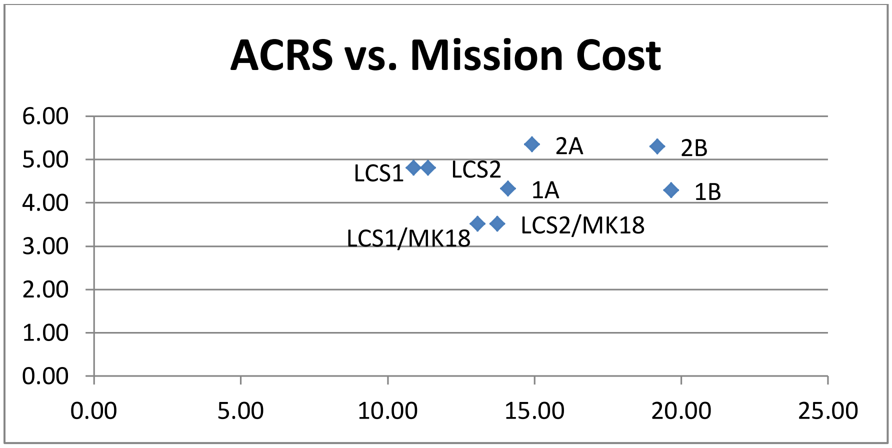

Figure 44. ACRS Baseline vs. Cost (2 MK18 Mod 2)

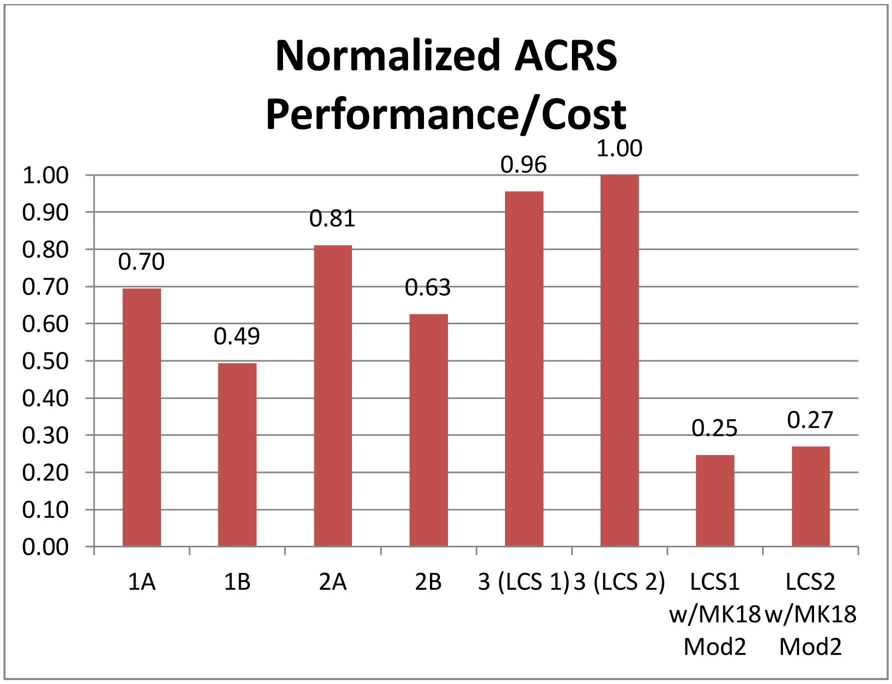

Figure 45. Normalized ACRS Baseline vs. Cost (2 MK18 Mod 2)

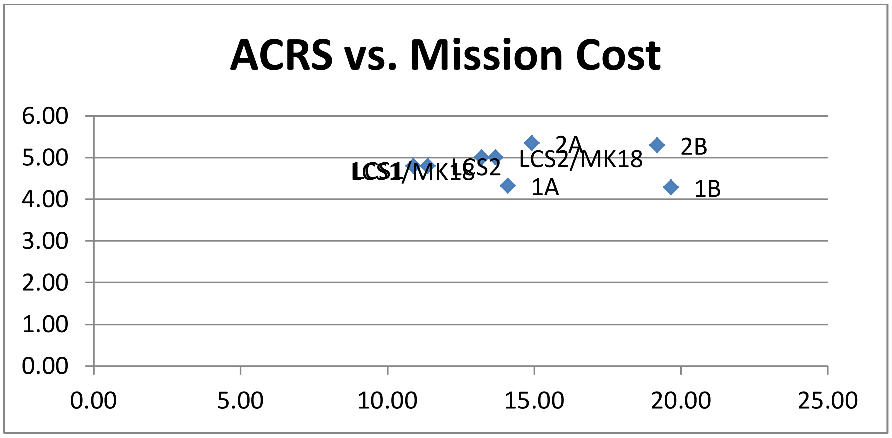

Figure 46. ACRS Baseline vs. Cost (3 MK18 Mod 2)

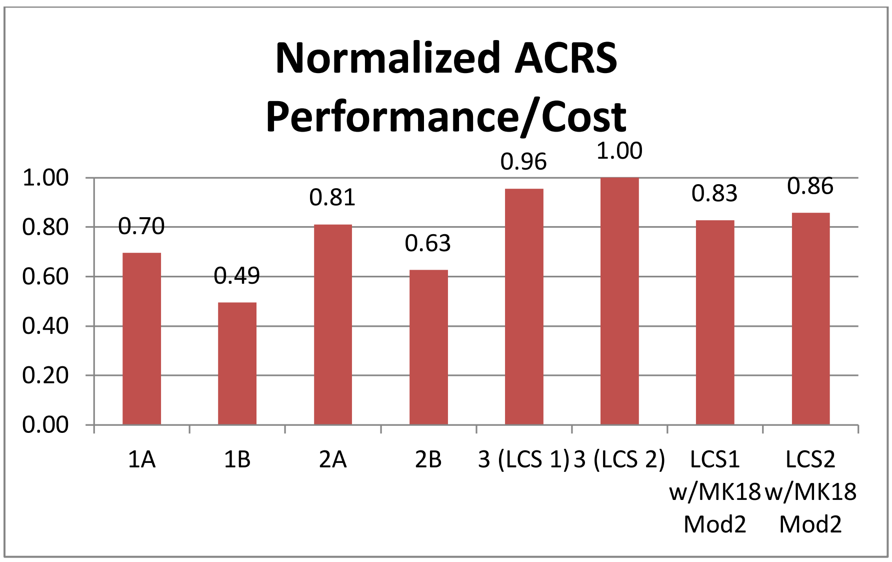

Figure 47. Normalized ACRS Baseline vs. Cost (3 MK18 Mod 2)

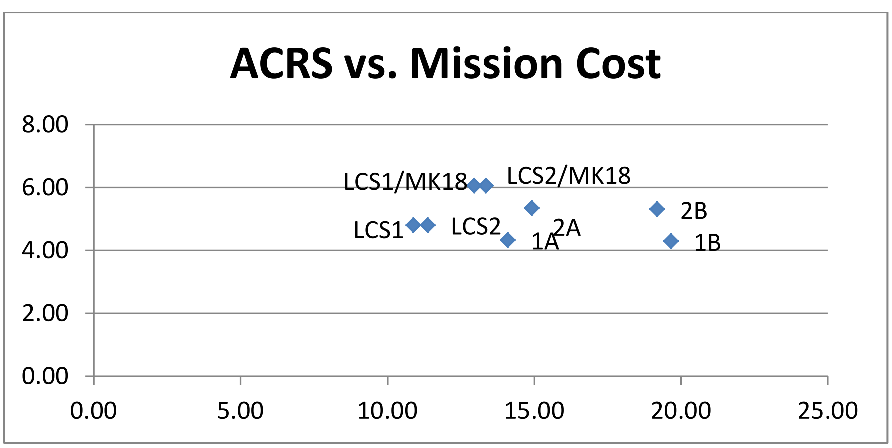

Figure 48. ACRS Baseline vs. Cost (4 MK18 Mod 2)

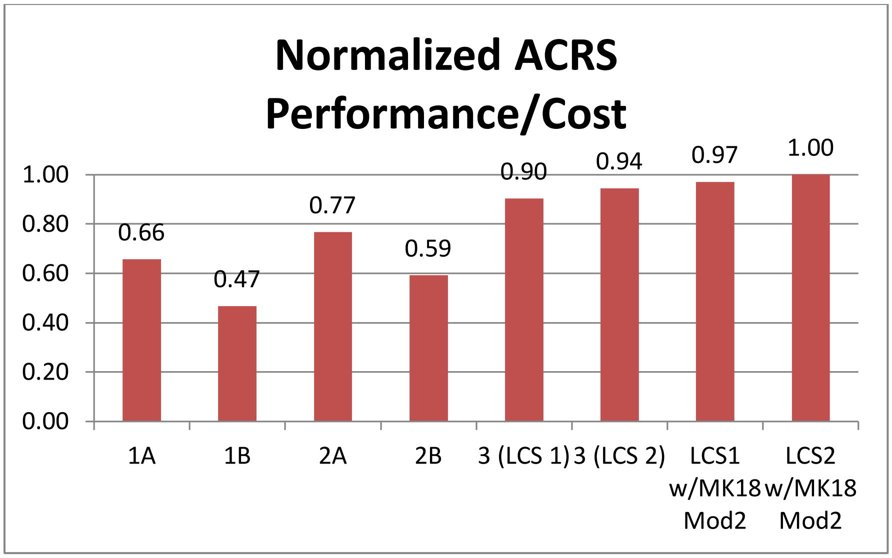

Figure 49. Normalized ACRS Baseline vs. Cost (4 MK18 Mod 2)

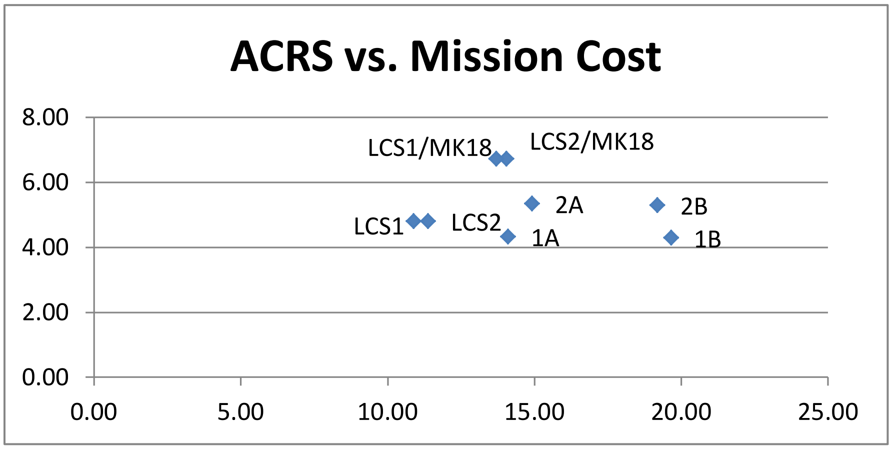

Figure 50. ACRS Baseline vs. Cost (5 MK18 Mod 2)

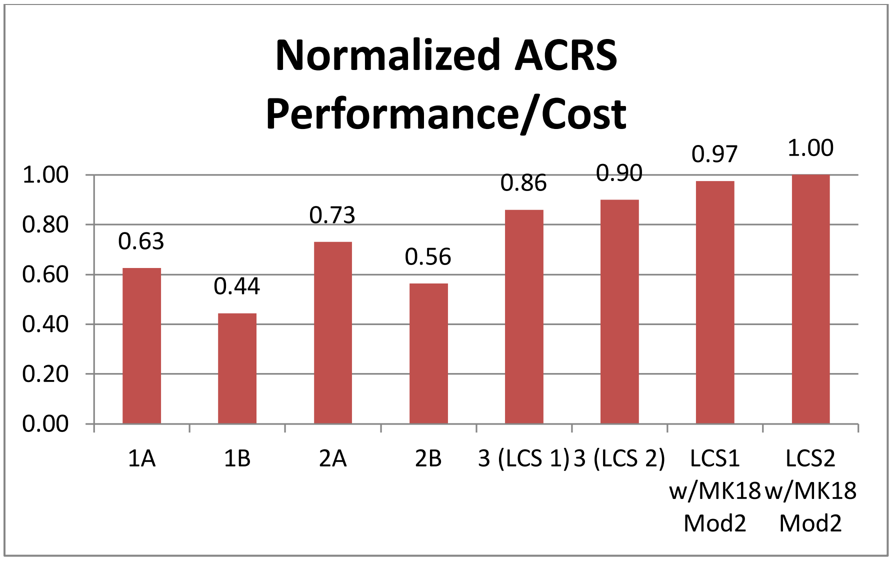

Figure 51. Normalized ACRS Baseline vs. Cost (5 MK18 Mod 2)

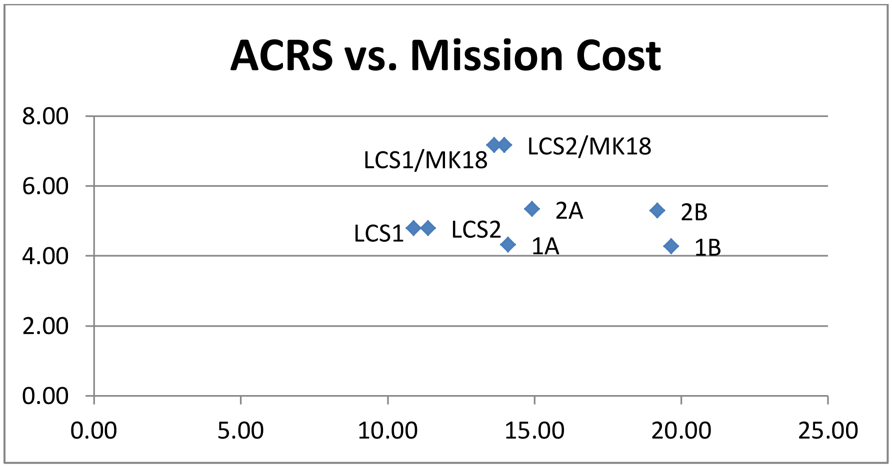

Figure 52. ACRS Baseline vs. Cost (6 MK18 Mod 2)

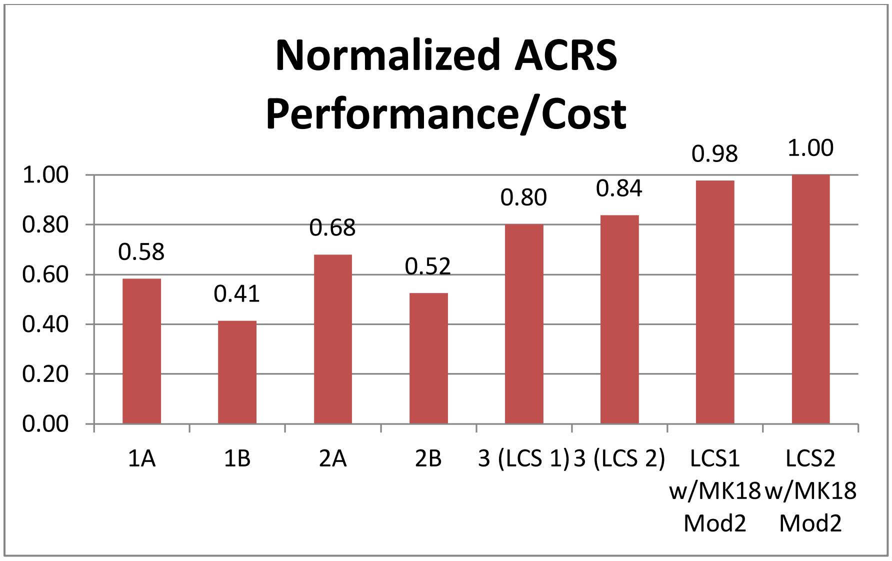

Figure 53. Normalized ACRS Baseline vs. Cost (6 MK18 Mod 2)

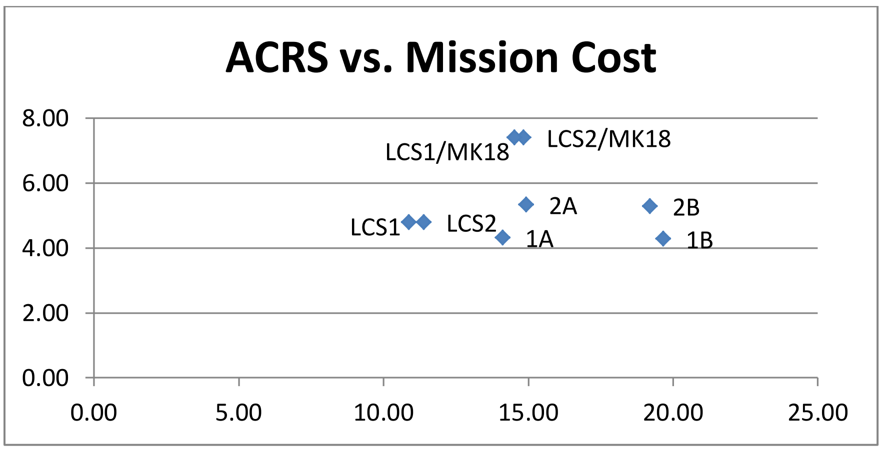

Figure 54. ACRS Baseline vs. Cost (7 MK18 Mod 2)

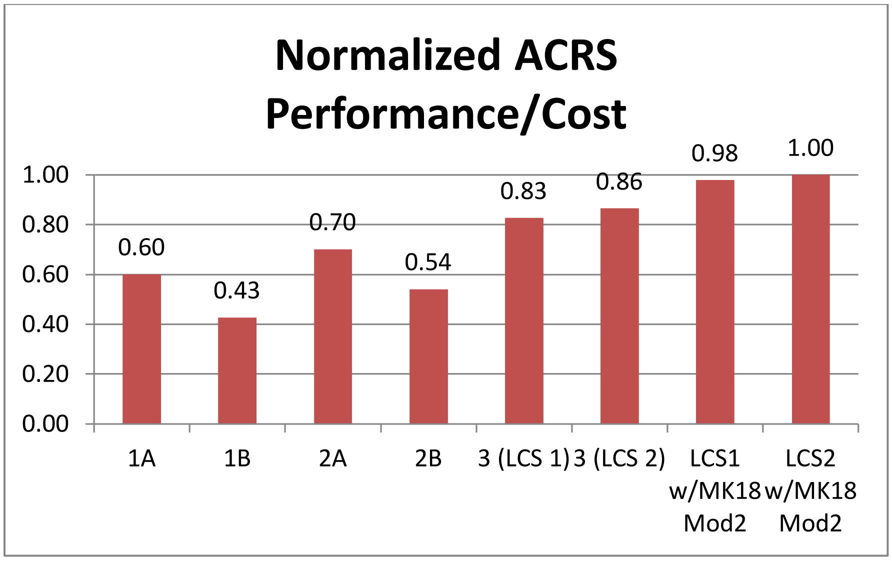

Figure 55. Normalized ACRS Baseline vs. Cost (7 MK18 Mod 2)

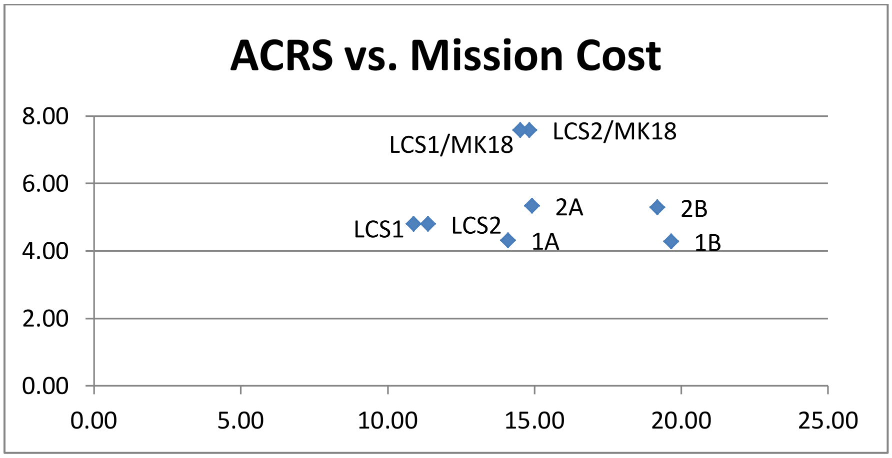

Figure 56. ACRS Baseline vs. Cost (8 MK18 Mod 2)

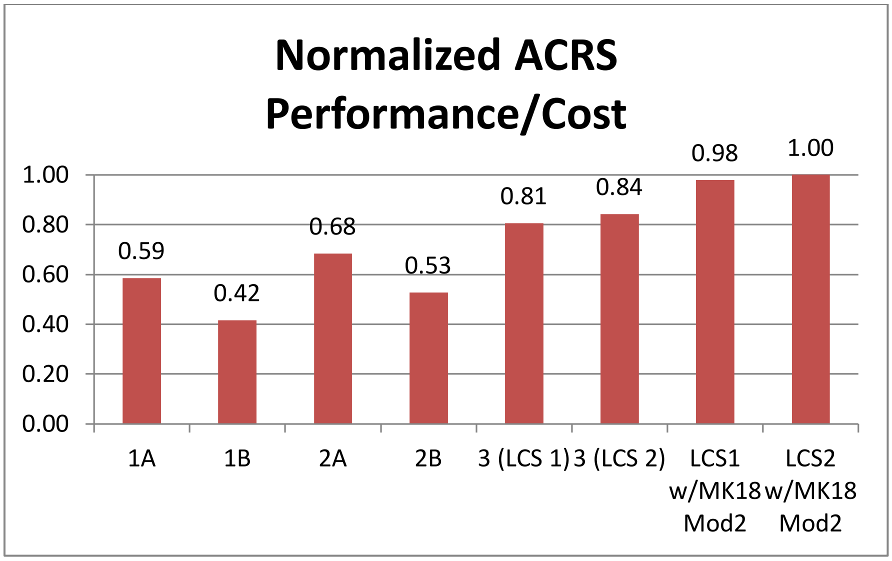

Figure 57. Normalized ACRS Baseline vs. Cost (8 MK18 Mod 2)

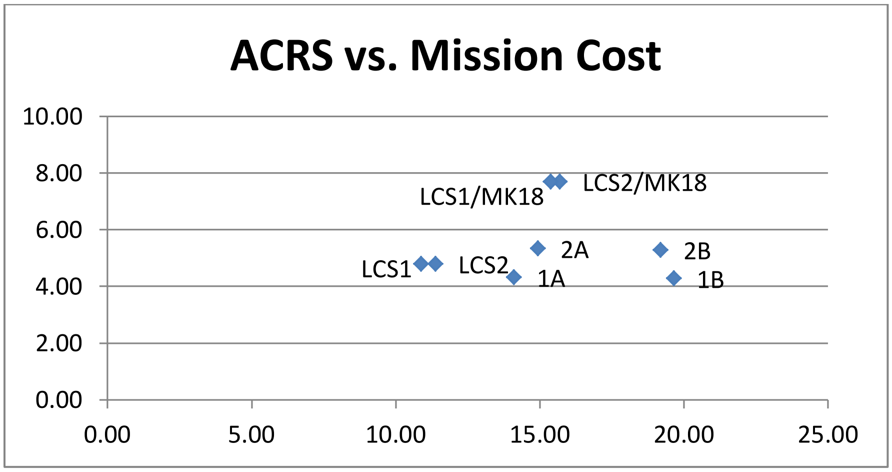

Figure 58. ACRS Baseline vs. Cost (9 MK18 Mod 2)

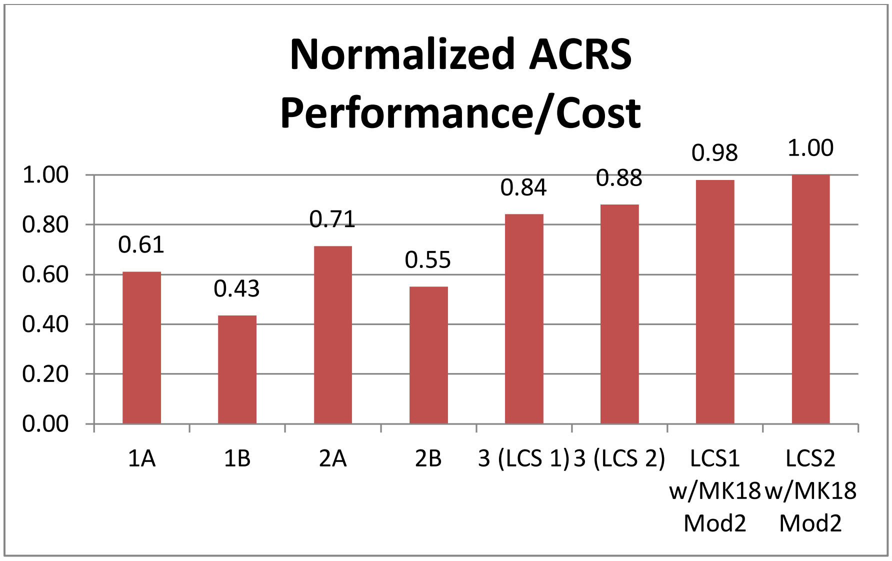

Figure 59. Normalized ACRS Baseline vs. Cost (9 MK18 Mod 2)

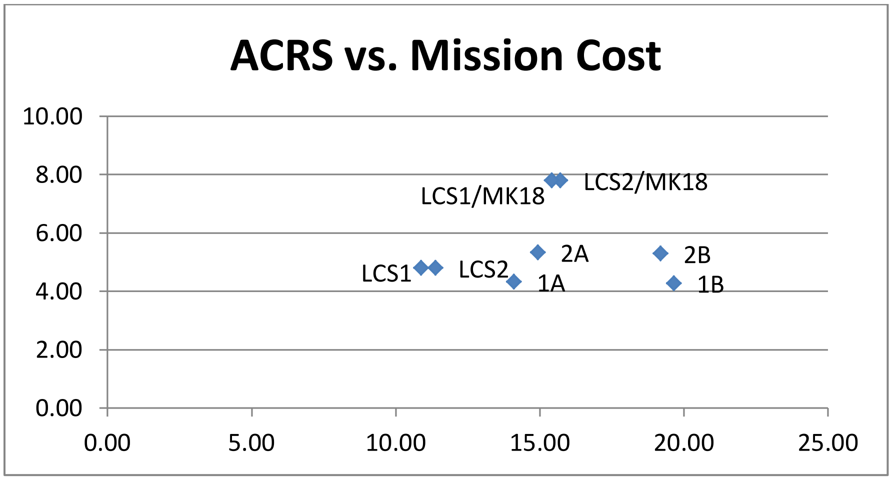

Figure 60. ACRS Baseline vs. Cost (10 MK18 Mod 2)

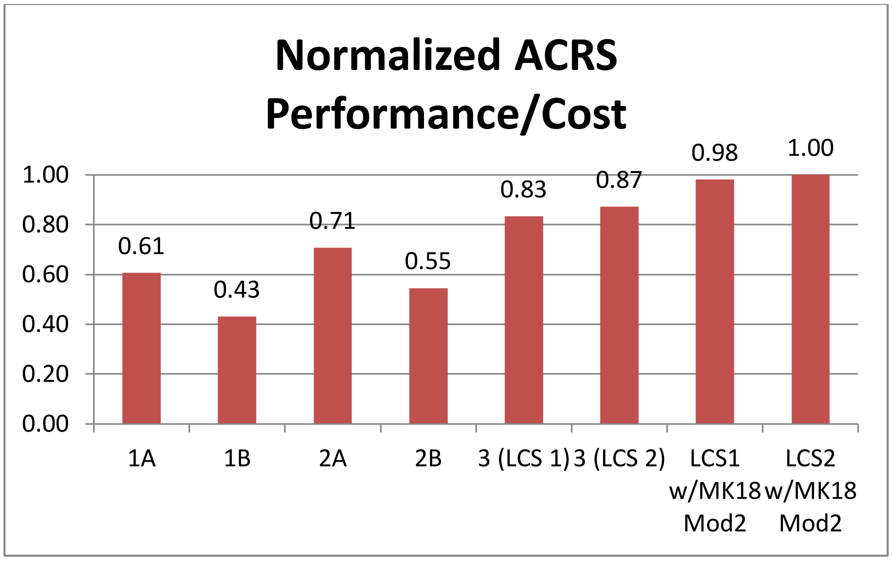

Figure 61. Normalized ACRS Baseline vs. Cost (10 MK18 Mod 2)

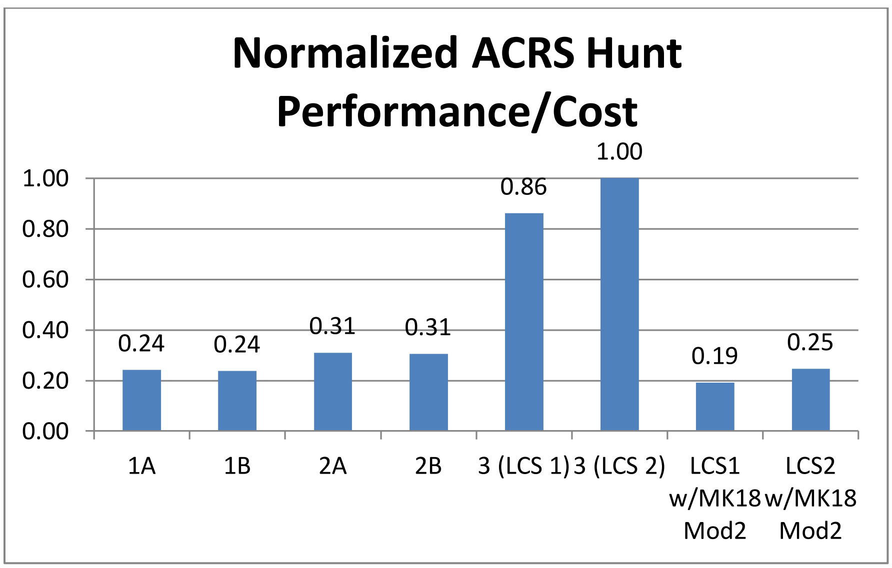

Figure 62. Normalized ACRS Hunt vs. Mission Cost (1 MK18 Mod 2)

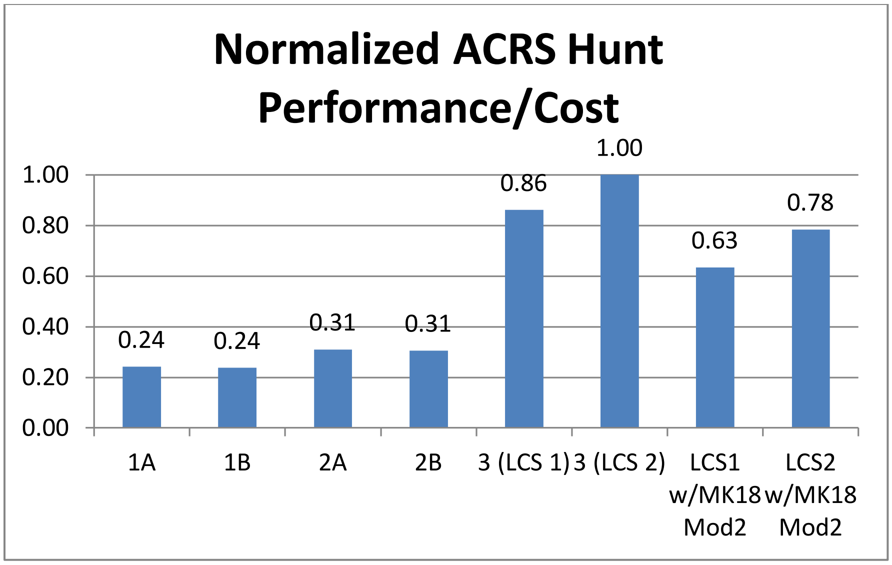

Figure 63. Normalized ACRS Hunt vs. Mission Cost (2 MK18 Mod 2)

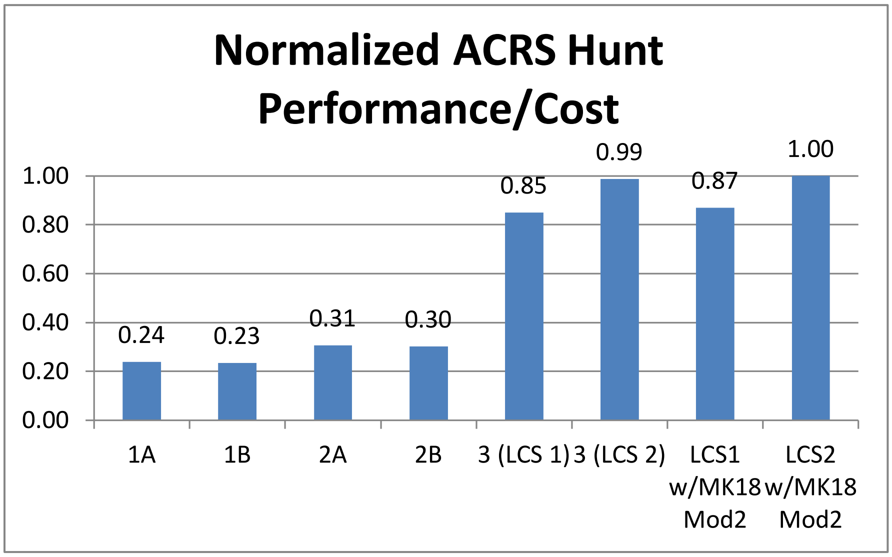

Figure 64. Normalized ACRS Hunt vs. Mission Cost (3 MK18 Mod 2)

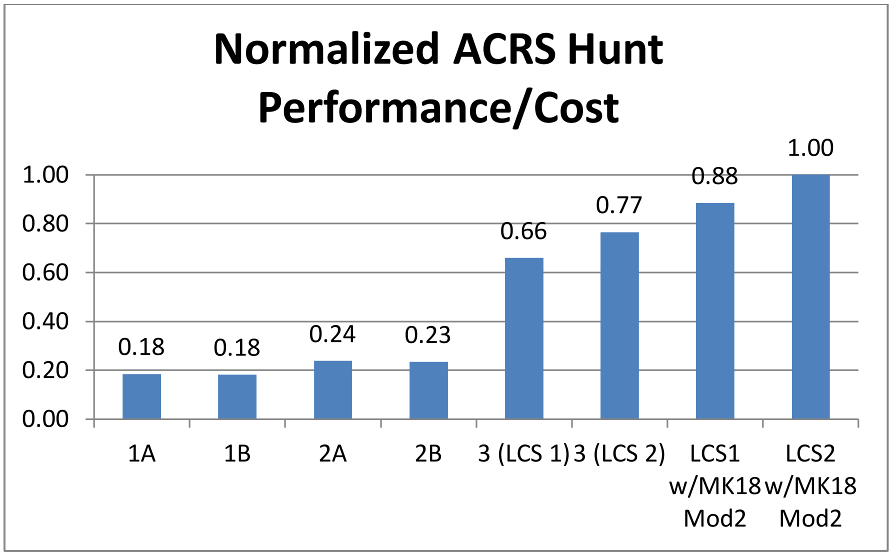

Figure 65. Normalized ACRS Hunt vs. Mission Cost (4 MK18 Mod 2)

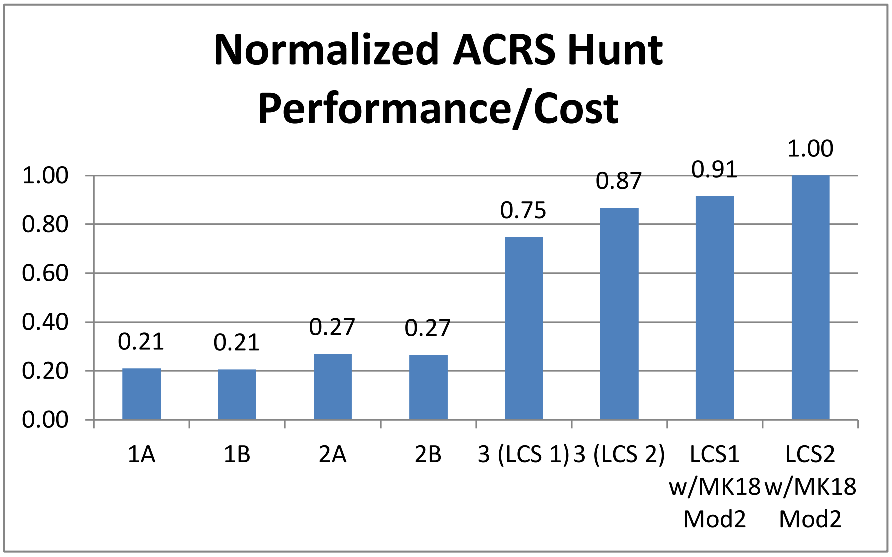

Figure 66. Normalized ACRS Hunt vs. Mission Cost (5 MK18 Mod 2)

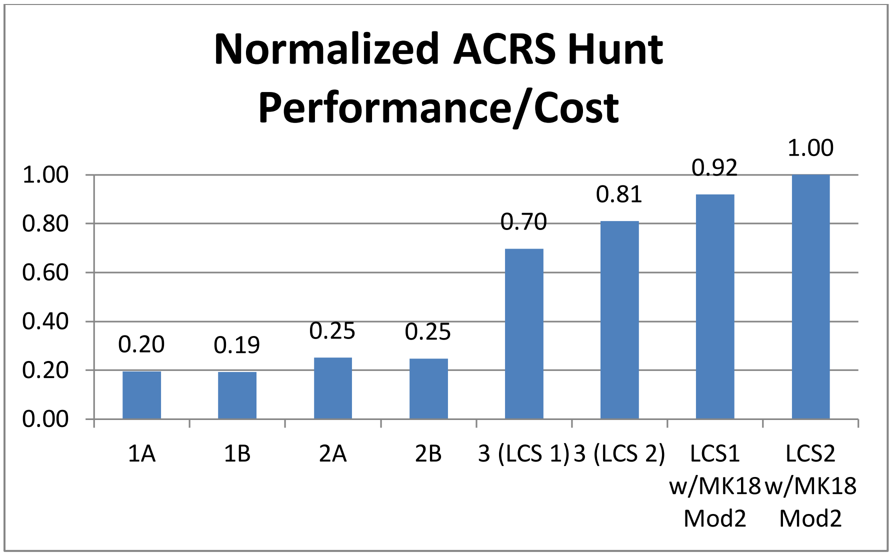

Figure 67. Normalized ACRS Hunt vs. Mission Cost (6 MK18 Mod 2)

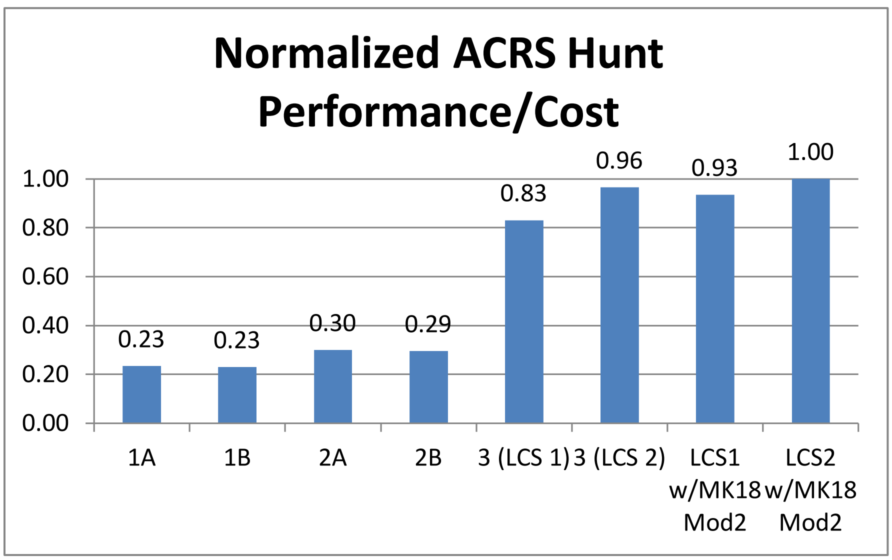

Figure 68. Normalized ACRS Hunt vs. Mission Cost (7 MK18 Mod 2)

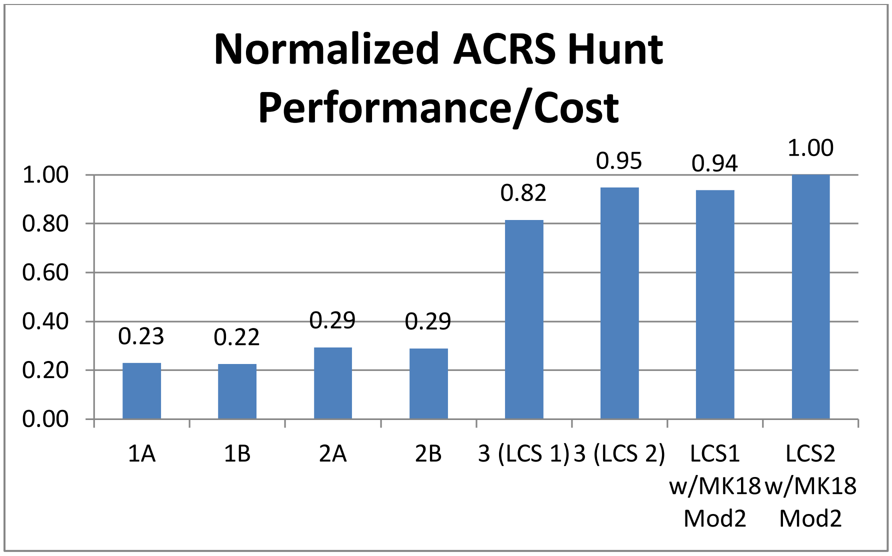

Figure 69. Normalized ACRS Hunt vs. Mission Cost (8 MK18 Mod 2)

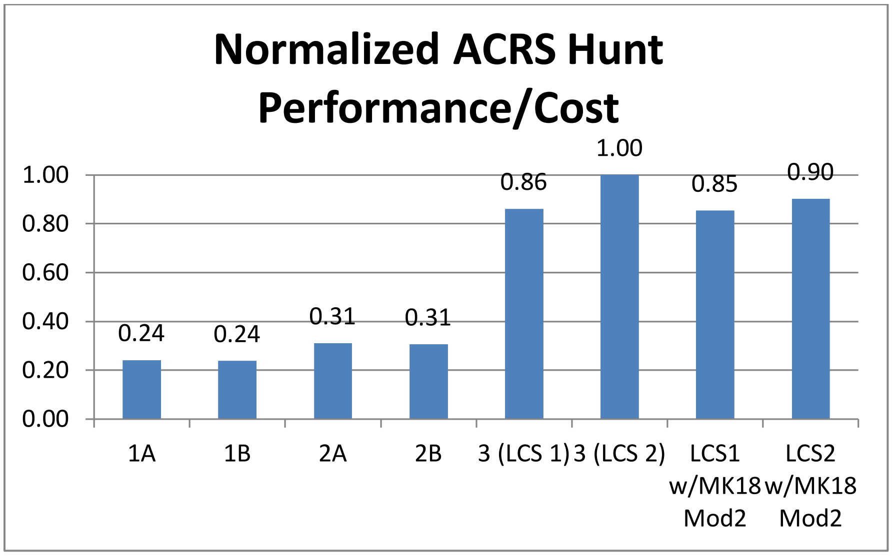

Figure 70. Normalized ACRS Hunt vs. Mission Cost (9 MK18 Mod 2)

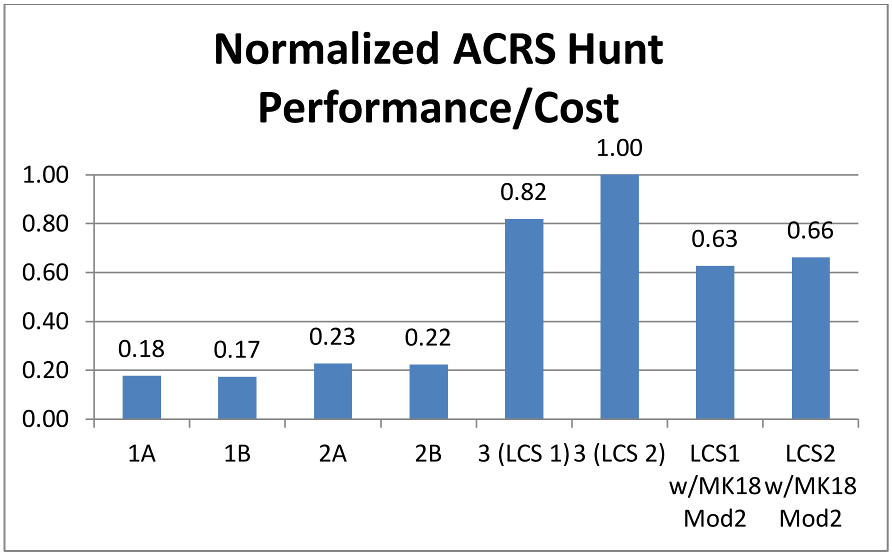

Figure 71. Normalized ACRS Hunt vs. Mission Cost (10 MK18 Mod 2)

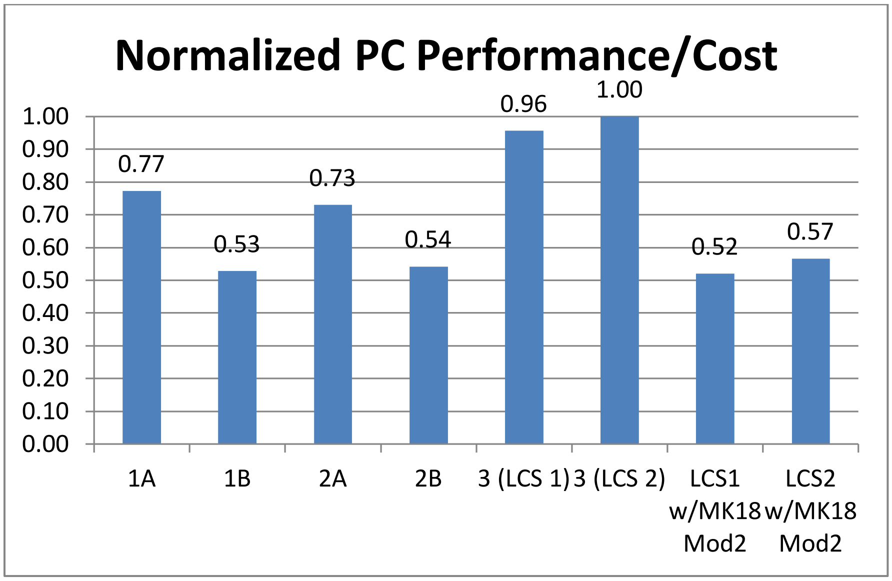

Figure 72. Normalized % Clearance vs. Mission Cost (1 MK18 Mod 2)

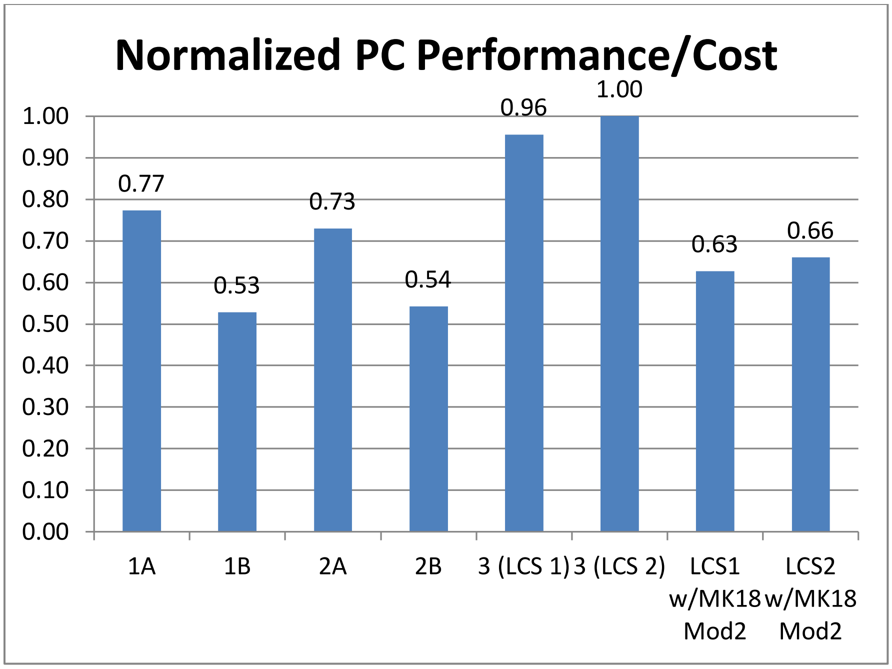

Figure 73. Normalized % Clearance vs. Mission Cost (2 MK18 Mod 2)

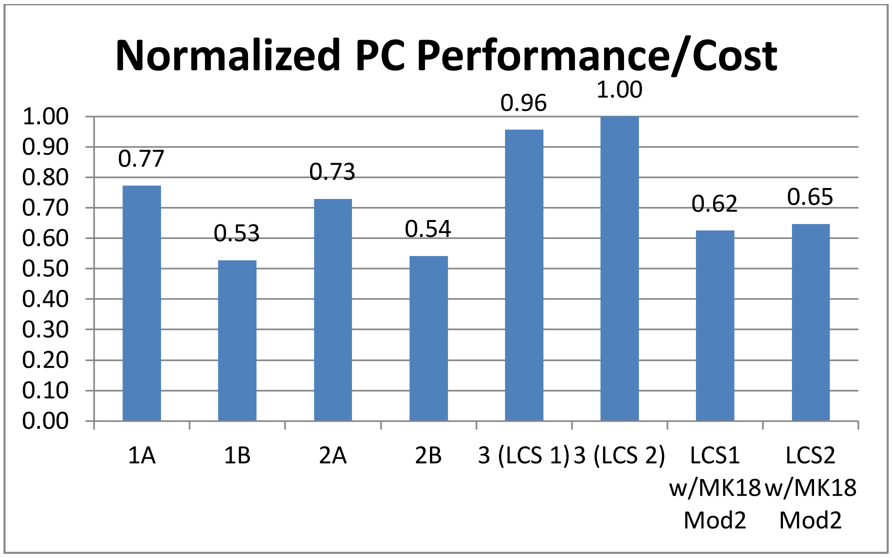

Figure 74. Normalized % Clearance vs. Mission Cost (3 MK18 Mod 2)

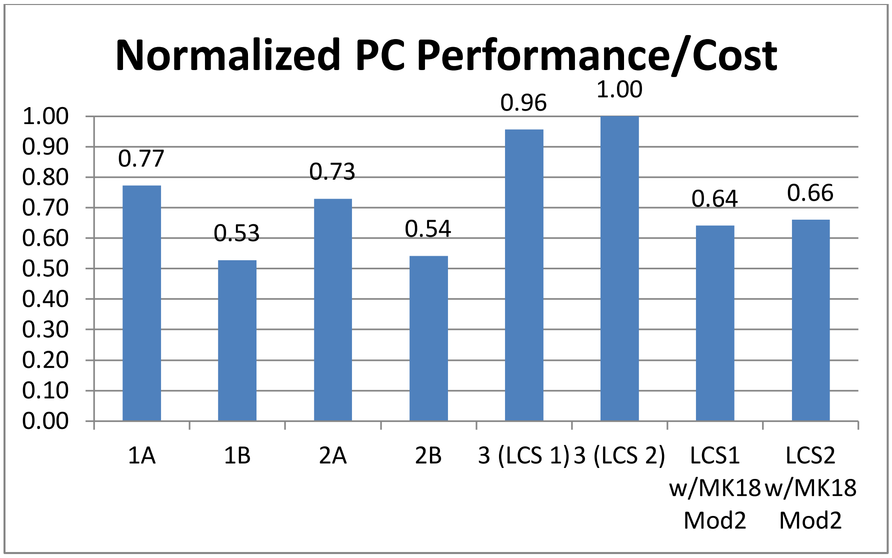

Figure 75. Normalized % Clearance vs. Mission Cost (4 MK18 Mod 2)

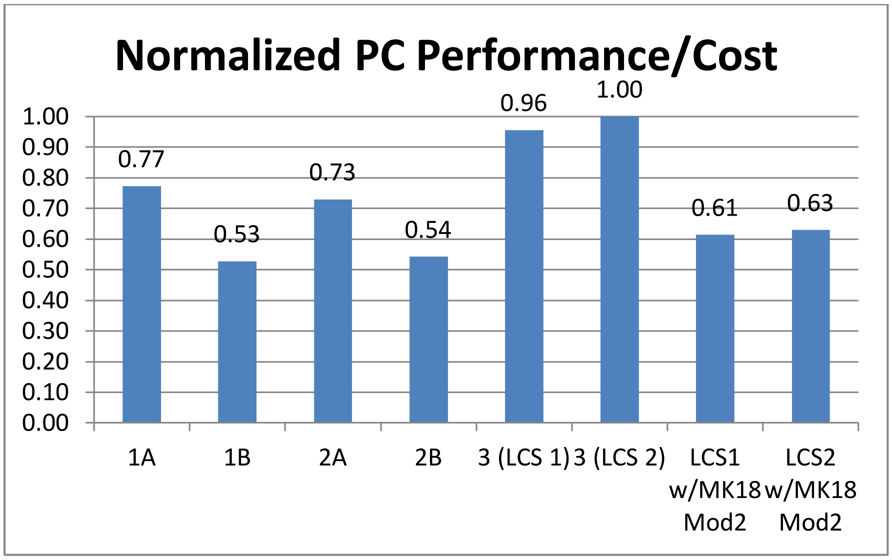

Figure 76. Normalized % Clearance vs. Mission Cost (5 MK18 Mod 2)

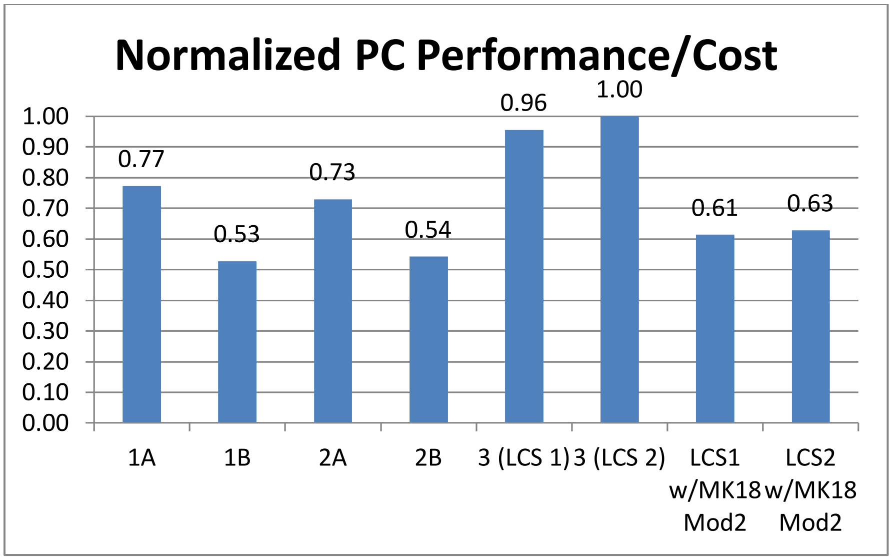

Figure 77. Normalized % Clearance vs. Mission Cost (6 MK18 Mod 2)

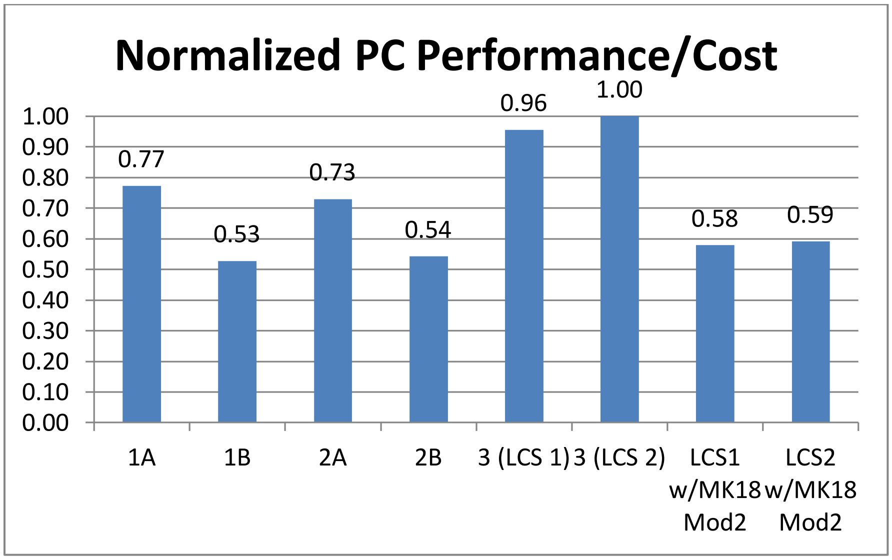

Figure 78. Normalized % Clearance vs. Mission Cost (7 MK18 Mod 2)

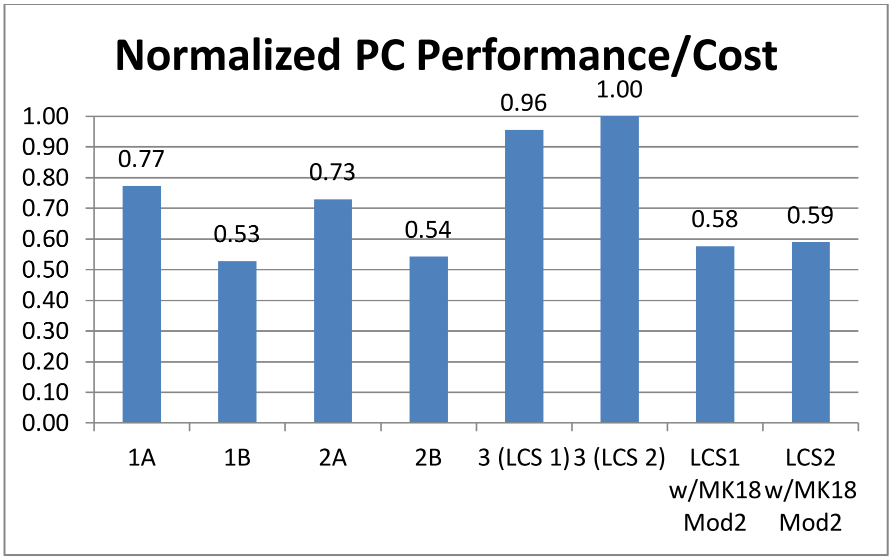

Figure 79. Normalized % Clearance vs. Mission Cost (8 MK18 Mod 2)

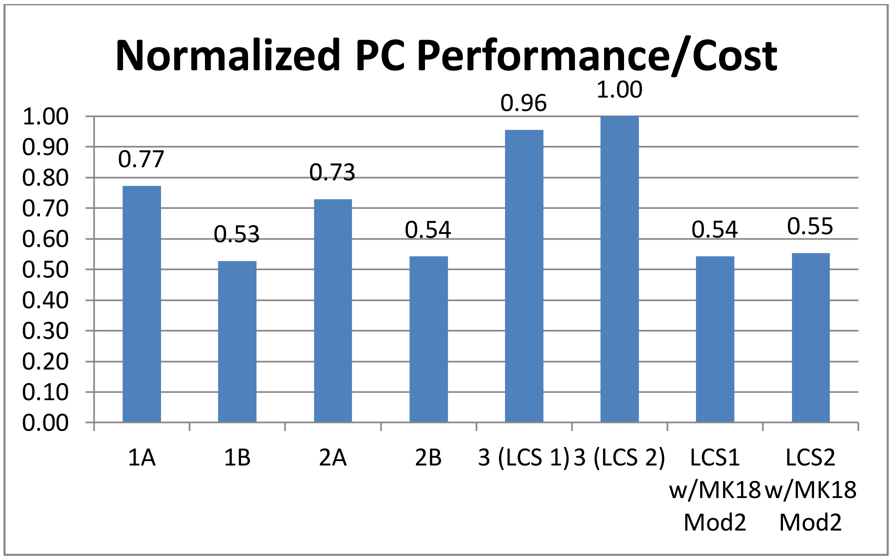

Figure 80. Normalized % Clearance vs. Mission Cost (9 MK18 Mod 2)

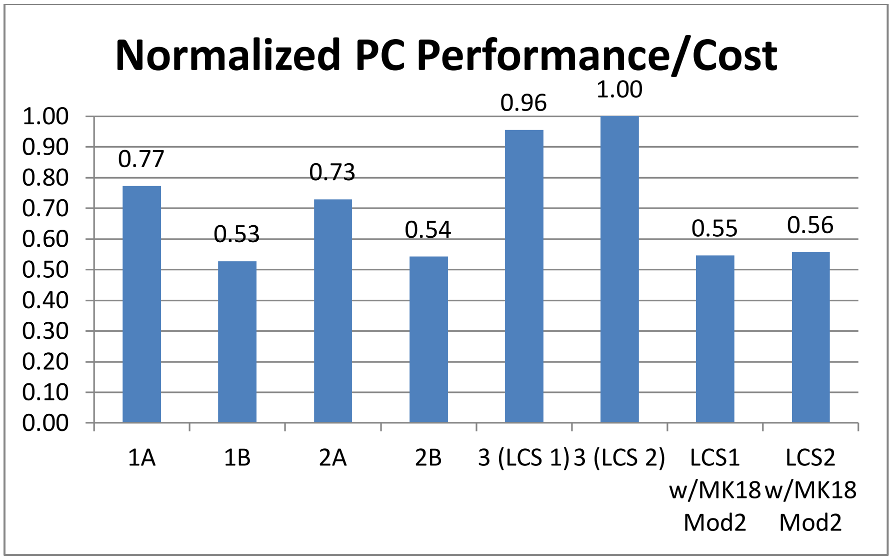

Figure 81. Normalized % Clearance vs. Mission Cost (10 MK18 Mod 2)

Table 29. Baseline Costs (1 MK18 Mod 2)

1 MK18 Mod2 BASELINE & HUNT Cost										
Configuration (4 MK18 Mod2)	Average Mission Time (hours)	Average Flight Time (hours)	Average # Surface Neutralizers	Average # Airborne Neutralizers	Total Ship O&S Cost (CY15$M)	Total MK18 Mod2 O&S Cost (CY15$M)	Total Helicopter O&S Cost (CY15$M)	Total Neutralizer Cost (CY15$M)	Total Estimated Cost (CY15$M)	Total Estimated Hunt Cost (CY15$M)
1A	574.31	72.26	48.56	0.00	11.56	0.00	2.06	0.50	14.12	11.56
1B	578.81	72.26	100.45	0.00	11.65	0.00	2.06	5.95	19.66	11.65
2A	469.71	124.66	36.40	32.78	9.45	0.00	3.33	2.16	14.94	11.11
2B	473.58	124.47	74.49	32.62	9.53	0.00	3.32	6.35	19.20	11.19
3 (LCS 1)	528.10	235.85	0.00	128.38	1.93	0.00	1.67	7.79	11.39	3.60
3 (LCS 2)	528.10	235.85	0.00	128.38	1.43	0.00	1.67	7.79	10.89	3.10
LCS1 w/MK18 Mod2	1415.85	272.70	0.00	137.62	5.18	0.88	2.09	8.35	16.51	6.06
LCS2 w/MK18 Mod2	1415.85	272.70	0.00	137.62	3.84	0.88	2.09	8.35	15.17	4.72

Table 30. Baseline Costs (2 MK18 Mod 2)

2 MK18 Mod2 BASELINE & HUNT Cost										
Configuration (4 MK18 Mod2)	Average Mission Time (hours)	Average Flight Time (hours)	Average # Surface Neutralizers	Average # Airborne Neutralizers	Total Ship O&S Cost (CY15$M)	Total MK18 Mod2 O&S Cost (CY15$M)	Total Helicopter O&S Cost (CY15$M)	Total Neutralizer Cost (CY15$M)	Total Estimated Cost (CY15$M)	Total Estimated Hunt Cost (CY15$M)
1A	574.31	72.26	48.56	0.00	11.56	0.00	2.06	0.50	14.12	11.56
1B	578.81	72.26	100.45	0.00	11.65	0.00	2.06	5.95	19.66	11.65
2A	469.71	124.66	36.40	32.78	9.45	0.00	3.33	2.16	14.94	11.11
2B	473.58	124.47	74.49	32.62	9.53	0.00	3.32	6.35	19.20	11.19
3 (LCS 1)	528.10	235.85	0.00	128.38	1.93	0.00	1.67	7.79	11.39	3.60
3 (LCS 2)	528.10	235.85	0.00	128.38	1.43	0.00	1.67	7.79	10.89	3.10
LCS1 w/MK18 Mod2	721.88	251.07	0.00	137.86	2.64	0.93	1.81	8.37	13.75	3.57
LCS2 w/MK18 Mod2	721.88	251.07	0.00	137.86	1.96	0.93	1.81	8.37	13.07	2.89

Table 31. Baseline Costs (3 MK18 Mod 2)

3 MK18 Mod2 BASELINE & HUNT Cost										
Configuration (4 MK18 Mod2)	Average Mission Time (hours)	Average Flight Time (hours)	Average # Surface Neutralizers	Average # Airborne Neutralizers	Total Ship O&S Cost (CY15$M)	Total MK18 Mod2 O&S Cost (CY15$M)	Total Helicopter O&S Cost (CY15$M)	Total Neutralizer Cost (CY15$M)	Total Estimated Cost (CY15$M)	Total Estimated Hunt Cost (CY15$M)
1A	574.31	72.26	48.56	0.00	11.56	0.00	2.06	0.50	14.12	11.56
1B	578.81	72.26	100.45	0.00	11.65	0.00	2.06	5.95	19.66	11.65
2A	469.71	124.66	36.40	32.78	9.45	0.00	3.33	2.16	14.94	11.11
2B	473.58	124.47	74.49	32.62	9.53	0.00	3.32	6.35	19.20	11.19
3 (LCS 1)	528.10	235.85	0.00	128.38	1.93	0.00	1.67	7.79	11.39	3.60
3 (LCS 2)	528.10	235.85	0.00	128.38	1.43	0.00	1.67	7.79	10.89	3.10
LCS1 w/MK18 Mod2	503.21	241.17	0.00	137.40	1.84	1.82	1.70	8.34	13.70	3.66
LCS2 w/MK18 Mod2	503.21	241.17	0.00	137.40	1.36	1.82	1.70	8.34	13.22	3.18

Table 32. Baseline Costs (4 MK18 Mod 2)

4 MK18 Mod2 BASELINE & HUNT Cost										
Configuration (4 MK18 Mod2)	Average Mission Time (hours)	Average Flight Time (hours)	Average # Surface Neutralizers	Average # Airborne Neutralizers	Total Ship O&S Cost (CY15$M)	Total MK18 Mod2 O&S Cost (CY15$M)	Total Helicopter O&S Cost (CY15$M)	Total Neutralizer Cost (CY15$M)	Total Estimated Cost (CY15$M)	Total Estimated Hunt Cost (CY15$M)
1A	574.31	72.26	48.56	0.00	11.56	0.00	2.06	0.50	14.12	11.56
1B	578.81	72.26	100.45	0.00	11.65	0.00	2.06	5.95	19.66	11.65
2A	469.71	124.66	36.40	32.78	9.45	0.00	3.33	2.16	14.94	11.11
2B	473.58	124.47	74.49	32.62	9.53	0.00	3.32	6.35	19.20	11.19
3 (LCS 1)	528.10	235.85	0.00	128.38	1.93	0.00	1.67	7.79	11.39	3.60
3 (LCS 2)	528.10	235.85	0.00	128.38	1.43	0.00	1.67	7.79	10.89	3.10
LCS1 w/MK18 Mod2	412.97	235.34	0.00	137.38	1.51	1.87	1.64	8.34	13.36	3.38
LCS2 w/MK18 Mod2	412.97	235.34	0.00	137.38	1.12	1.87	1.64	8.34	12.97	2.99

Table 33. Baseline Costs (5 MK18 Mod 2)

5 MK18 Mod2 BASELINE & HUNT Cost										
Configuration (4 MK18 Mod2)	Average Mission Time (hours)	Average Flight Time (hours)	Average # Surface Neutralizers	Average # Airborne Neutralizers	Total Ship O&S Cost (CY15$M)	Total MK18 Mod2 O&S Cost (CY15$M)	Total Helicopter O&S Cost (CY15$M)	Total Neutralizer Cost (CY15$M)	Total Estimated Cost (CY15$M)	Total Estimated Hunt Cost (CY15$M)
1A	574.31	72.26	48.56	0.00	11.56	0.00	2.06	0.50	14.12	11.56
1B	578.81	72.26	100.45	0.00	11.65	0.00	2.06	5.95	19.66	11.65
2A	469.71	124.66	36.40	32.78	9.45	0.00	3.33	2.16	14.94	11.11
2B	473.58	124.47	74.49	32.62	9.53	0.00	3.32	6.35	19.20	11.19
3 (LCS 1)	528.10	235.85	0.00	128.38	1.93	0.00	1.67	7.79	11.39	3.60
3 (LCS 2)	528.10	235.85	0.00	128.38	1.43	0.00	1.67	7.79	10.89	3.10
LCS1 w/MK18 Mod2	372.12	231.83	0.00	137.40	1.36	2.75	1.61	8.34	14.06	4.12
LCS2 w/MK18 Mod2	372.12	231.83	0.00	137.40	1.01	2.75	1.61	8.34	13.71	3.76

Table 34. Baseline Costs (6 MK18 Mod 2)

6 MK18 Mod2 BASELINE & HUNT Cost										
Configuration (4 MK18 Mod2)	Average Mission Time (hours)	Average Flight Time (hours)	Average # Surface Neutralizers	Average # Airborne Neutralizers	Total Ship O&S Cost (CY15$M)	Total MK18 Mod2 O&S Cost (CY15$M)	Total Helicopter O&S Cost (CY15$M)	Total Neutralizer Cost (CY15$M)	Total Estimated Cost (CY15$M)	Total Estimated Hunt Cost (CY15$M)
1A	574.31	72.26	48.56	0.00	11.56	0.00	2.06	0.50	14.12	11.56
1B	578.81	72.26	100.45	0.00	11.65	0.00	2.06	5.95	19.66	11.65
2A	469.71	124.66	36.40	32.78	9.45	0.00	3.33	2.16	14.94	11.11
2B	473.58	124.47	74.49	32.62	9.53	0.00	3.32	6.35	19.20	11.19
3 (LCS 1)	528.10	235.85	0.00	128.38	1.93	0.00	1.67	7.79	11.39	3.60
3 (LCS 2)	528.10	235.85	0.00	128.38	1.43	0.00	1.67	7.79	10.89	3.10
LCS1 w/MK18 Mod2	350.17	228.04	0.00	136.98	1.28	2.80	1.58	8.32	13.98	4.08
LCS2 w/MK18 Mod2	350.17	228.04	0.00	136.98	0.95	2.80	1.58	8.32	13.65	3.75

Table 35. Baseline Costs (7 MK18 Mod 2)

7 MK18 Mod2 BASELINE & HUNT Cost										
Configuration (4 MK18 Mod2)	Average Mission Time (hours)	Average Flight Time (hours)	Average # Surface Neutralizers	Average # Airborne Neutralizers	Total Ship O&S Cost (CY15$M)	Total MK18 Mod2 O&S Cost (CY15$M)	Total Helicopter O&S Cost (CY15$M)	Total Neutralizer Cost (CY15$M)	Total Estimated Cost (CY15$M)	Total Estimated Hunt Cost (CY15$M)
1A	574.31	72.26	48.56	0.00	11.56	0.00	2.06	0.50	14.12	11.56
1B	578.81	72.26	100.45	0.00	11.65	0.00	2.06	5.95	19.66	11.65
2A	469.71	124.66	36.40	32.78	9.45	0.00	3.33	2.16	14.94	11.11
2B	473.58	124.47	74.49	32.62	9.53	0.00	3.32	6.35	19.20	11.19
3 (LCS 1)	528.10	235.85	0.00	128.38	1.93	0.00	1.67	7.79	11.39	3.60
3 (LCS 2)	528.10	235.85	0.00	128.38	1.43	0.00	1.67	7.79	10.89	3.10
LCS2 w/MK18 Mod2	340.62	226.46	0.00	137.54	1.25	3.69	1.57	8.35	14.85	4.93
LCS1 w/MK18 Mod2	340.62	226.46	0.00	137.54	0.92	3.69	1.57	8.35	14.53	4.61

Table 36. Baseline Costs (8 MK18 Mod 2)

8 MK18 Mod2 BASELINE & HUNT Cost										
Configuration (4 MK18 Mod2)	Average Mission Time (hours)	Average Flight Time (hours)	Average # Surface Neutralizers	Average # Airborne Neutralizers	Total Ship O&S Cost (CY15$M)	Total MK18 Mod2 O&S Cost (CY15$M)	Total Helicopter O&S Cost (CY15$M)	Total Neutralizer Cost (CY15$M)	Total Estimated Cost (CY15$M)	Total Estimated Hunt Cost (CY15$M)
1A	574.31	72.26	48.56	0.00	11.56	0.00	2.06	0.50	14.12	11.56
1B	578.81	72.26	100.45	0.00	11.65	0.00	2.06	5.95	19.66	11.65
2A	469.71	124.66	36.40	32.78	9.45	0.00	3.33	2.16	14.94	11.11
2B	473.58	124.47	74.49	32.62	9.53	0.00	3.32	6.35	19.20	11.19
3 (LCS 1)	528.10	235.85	0.00	128.38	1.93	0.00	1.67	7.79	11.39	3.60
3 (LCS 2)	528.10	235.85	0.00	128.38	1.43	0.00	1.67	7.79	10.89	3.10
LCS1 w/MK18 Mod2	333.48	223.73	0.00	137.27	1.22	3.74	1.55	8.33	14.84	4.96
LCS2 w/MK18 Mod2	333.48	223.73	0.00	137.27	0.90	3.74	1.55	8.33	14.52	4.64

Table 37. Baseline Costs (9 MK18 Mod 2)

9 MK18 Mod2 BASELINE & HUNT Cost										
Configuration (4 MK18 Mod2)	**Average Mission Time (hours)**	**Average Flight Time (hours)**	**Average # Surface Neutralizers**	**Average # Airborne Neutralizers**	**Total Ship O&S Cost (CY15$M)**	**Total MK18 Mod2 O&S Cost (CY15$M)**	**Total Helicopter O&S Cost (CY15$M)**	**Total Neutralizer Cost (CY15$M)**	**Total Estimated Cost (CY15$M)**	**Total Estimated Hunt Cost (CY15$M)**
1A	574.31	72.26	48.56	0.00	11.56	0.00	2.06	0.50	14.12	11.56
1B	578.81	72.26	100.45	0.00	11.65	0.00	2.06	5.95	19.66	11.65
2A	469.71	124.66	36.40	32.78	9.45	0.00	3.33	2.16	14.94	11.11
2B	473.58	124.47	74.49	32.62	9.53	0.00	3.32	6.35	19.20	11.19
3 (LCS 1)	528.10	235.85	0.00	128.38	1.93	0.00	1.67	7.79	11.39	3.60
3 (LCS 2)	528.10	235.85	0.00	128.38	1.43	0.00	1.67	7.79	10.89	3.10
LCS1 w/MK18 Mod2	329.05	222.04	0.00	137.25	1.20	4.62	1.53	8.33	15.69	5.83
LCS2 w/MK18 Mod2	329.05	222.04	0.00	137.25	0.89	4.62	1.53	8.33	15.38	5.52

Table 38. Baseline Costs (10 MK18 Mod 2)

10 MK18 Mod2 BASELINE & HUNT Cost										
Configuration (4 MK18 Mod2)	**Average Mission Time (hours)**	**Average Flight Time (hours)**	**Average # Surface Neutralizers**	**Average # Airborne Neutralizers**	**Total Ship O&S Cost (CY15$M)**	**Total MK18 Mod2 O&S Cost (CY15$M)**	**Total Helicopter O&S Cost (CY15$M)**	**Total Neutralizer Cost (CY15$M)**	**Total Estimated Cost (CY15$M)**	**Total Estimated Hunt Cost (CY15$M)**
1A	574.31	72.26	48.56	0.00	11.56	0.00	2.06	0.50	14.12	11.56
1B	578.81	72.26	100.45	0.00	11.65	0.00	2.06	5.95	19.66	11.65
2A	469.71	124.66	36.40	32.78	9.45	0.00	3.33	2.16	14.94	11.11
2B	473.58	124.47	74.49	32.62	9.53	0.00	3.32	6.35	19.20	11.19
3 (LCS 1)	528.10	235.85	0.00	128.38	1.93	0.00	1.67	7.79	11.39	2.76
3 (LCS 2)	528.10	235.85	0.00	128.38	1.43	0.00	1.67	7.79	10.89	2.27
LCS1 w/MK18 Mod2	325.51	220.28	0.00	137.34	1.19	4.67	1.52	8.34	15.72	5.86
LCS2 w/MK18 Mod2	325.51	220.28	0.00	137.34	0.88	4.67	1.52	8.34	15.42	5.56

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